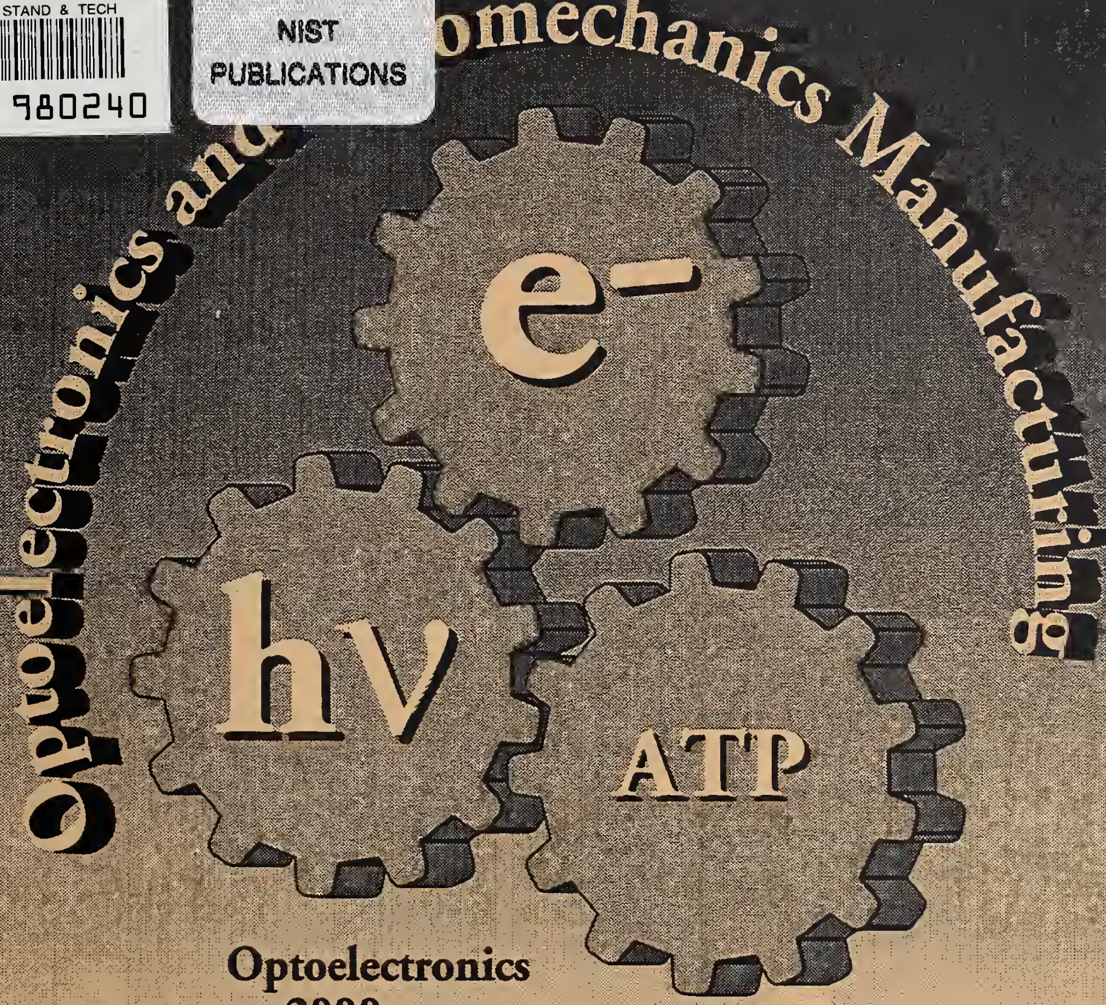

Optoelectronics
2000

A Focused Program Development Workshop

P r o c e e d i n g s

February 15, 1995
National Institute of
Standards and Technology
Gaithersburg, MD

T. Lettieri • V. McCrary • J. Boudreaux

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Optoelectronics and Optomechanics Manufacturing: An ATP Focused Program Development Workshop Proceedings - February 15, 1995

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Advanced Technology Program

National Institute of Standards and Technology
Gaithersburg, MD 20899

February 1996

U.S. Department of Commerce
Ronald Brown, Secretary

National Institute of Standards and Technology
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OPTOELECTRONICS AND OPTOMECHANICS MANUFACTURING

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OPTOELECTRONICS AND OPTOMECHANICS MANUFACTURING

Preface

The Advanced Technology Program (ATP) Workshop on Optoelectronics and Optomechanics Manufacturing was held at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland on February 15, 1995. The purpose of the Workshop was to respond to industry interest and provide an open forum for the exchange of ideas among interested members of the optics/photonics community concerning the strategic importance of optoelectronics (OE) and optomechanics (OM) technologies to U.S. economic growth. The Workshop brought together over 160 experts in OE/OM for the purpose of addressing the issues and requirements of U.S. industry in the area of OE/OM manufacturing.

Starting off the morning session were two invited overview presentations, one from Arpad Bergh of the Optoelectronics Industry Development Association (OIDA) and the other from Robert Kleiber of AT&T. The remainder of the morning session consisted of ten contributed White Papers, on topics ranging from Vertical Cavity Surface Emitting Lasers to OE packaging to polymeric OE materials. These presentations were selected from over thirty submitted White Papers. The afternoon session was devoted to six breakout groups in the following topics: business and economic issues; materials; design/modeling; devices/components; assemblies/applications; and testing/inspection. The breakout sessions provided an opportunity for all Workshop attendees to express their views and concerns about various issues in OE/OM manufacturing. Participants in the breakout sessions were asked to consider four questions: *what is the state of OE/OM manufacturing now?; where do we want to be in 7-8 years?; what technology developments/breakthroughs are needed to get there?; and what is the level of industry commitment in this area?* The discussions were often lively, and always interesting; the salient points of three breakout sessions are summarized within these Proceedings.

Input gained from the morning presentations and the breakout sessions will be used to help formulate the scope and range of a proposed ATP Focused Program in OE/OM manufacturing - Optoelectronics 2000. In addition, we welcome your input in helping plan our Focused Program. This can be accomplished by submitting a White Paper detailing your thoughts about OE/OM manufacturing. Information about the format for Optoelectronics 2000 Focused Program White Papers are included in these Proceedings; further details may be obtained by contacting any of the Workshop organizers listed below.

II. Introduction

Agenda

Workshop on Optoelectronics and Optomechanics Manufacturing

Advanced Technology Program
National Institute of Standards and Technology
Gaithersburg, MD
February 15, 1995

8:00 AM	Registration	
8:30 AM	Opening Remarks	Thomas Lettieri, NIST
8:45 AM	ATP Overview	Michael Daum, NIST
9:05 AM	The OIDA Roadmap	Arpad Bergh, OIDA
9:30 AM	The NEMI Roadmap	Robert Klaiber, AT&T
9:45 AM	White Paper Session	Jack Boudreaux, NIST
10:30 AM	Coffee Break	
10:45 AM	White Paper Session (cont'd)	Jack Boudreaux, NIST
12:45 PM	Lunch	
2:00 PM	Breakout Sessions*,+	

- Business/Economic Issues (M. Daum, C. Grinspon)
- Materials (V. McCrary, L. Rotter, A. Paul)
- Design/Modelling (J. Boudreaux, J. Marshall)
- Devices/Components (R. Marquardt, J. Pellegrino)
- Assemblies/Applications (D. Collins, J. Comas)
- Testing/Inspection (C. Cromer, C. Evans)

4:15 PM	Joint Session
5:00 PM	Adjourn

* Refreshments will be available after 2:30 PM near the registration desk.

+ Facilitators names in parentheses.

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ATP: Optoelectronics and Optomechanics Manufacturing
February 15, 1995
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Advanced Technology Program

U.S. Department of Commerce

Technology Administration

National Institute of Standards and Technology

Overview

Begun in 1990, the Advanced Technology Program at the National Institute of Standards and Technology invests directly in the nation's economic growth by working with industry to develop innovative technologies with strong commercial potential—technologies which, if successful, would enable novel or greatly improved products and services for the world market.

The ATP concentrates on promising, but high-risk, enabling technologies that can form the basis for new and improved products, manufacturing processes, and services. It accelerates technologies that, because they are risky, are unlikely to be developed in time to compete in rapidly changing world markets without such a partnership of industry and government. It does not fund product development.

Essential Features

The unique mission of the ATP—support for civilian technologies in the nation's economic interest—requires some special features, which have become hallmarks of the ATP and major factors in its success.

The ATP has a broad mission to promote large economic benefits for the nation.

The legislative mandate of the ATP is to promote "commercializing new scientific discoveries rapidly" and "refining manufacturing practices." This offers tremendous scope. The objective of some projects is to develop technologies that enable lower cost, higher quality, or faster-to-market products. The ultimate objective of others is to develop the know-how to provide new-to-the-world or radically improved products and services. The ATP has a high potential impact on U.S. economic growth because, unlike other federal technology programs, it makes investments explicitly for this reason rather than for some other national goal.

The ATP works as a partner with industry.

While government provides the catalyst, industry *conceives, partially funds, and executes* ATP projects. Management of projects is geared to ensure that the work performed is what industry believes should be done and is what it can do best.

The ATP relies on the substantial involvement of industry to define and implement its R&D programs. ATP research directions are selected based on suggestions from industry and developed in consultation with industry. Specific R&D projects are selected from proposals developed and submitted by industry. All awards are made through announced competitions.

The ATP emphasizes cost sharing—ATP recipients on average pay more than half the total costs of the R&D. This helps ensure that companies have a vested interest in the success of projects and in timely commercialization. At the same time, participation by small companies and start-ups is not precluded, because the single-applicant requirement for cost sharing is that the company cover its indirect costs. Since most start-ups and small companies have low indirect cost rates, this requirement is not prohibitive.

The ATP also takes an active role in helping to ensure the success of the projects it supports. ATP program managers work to build close, cooperative relationships with their counterparts in industry.

Projects are selected on the basis of both technical and business merit through a fair and rigorous competition.

Each proposal is reviewed thoroughly by scientists and engineers expert in the subject area—a common procedure for government technology programs. But ATP proposals that score well in this technical review go on to a *further* evaluation of potential economic impact, evidence of significant commitment to the project on the part of the proposer, and other business-related factors affecting the likelihood that successful results will be commercialized.

The scientific and technical reviewers are primarily federal and academic experts to avoid conflict-of-interest problems and protect proprietary information. Business reviews are conducted primarily by business experts from the private sector who agree to avoid conflicts of interest and abide by non-disclosure requirements. Semifinalists receive in-depth oral reviews. Proposals are ranked according to published selection criteria, and funding is awarded on the basis of the ranking. This merit-based selection process has been fully tested and refined and is essential to the effectiveness of the ATP.

The ATP provides direct support to for-profit companies of all sizes.

Commercial firms know best how to commercialize a promising new technology. With this in mind, the ATP funds for-profit companies. Small, medium, and large companies, and joint ventures led by two or more companies, are eligible for direct funding. Successful ATP project sponsors range in size from start-up companies with a handful of employees to major industrial firms with international scope. Universities, federal laboratories, and non-profit independent research organizations participate in many ATP projects, but as subcontractors or as members of joint ventures (non-profit independent research organizations may *administer* joint ventures).

The ATP has a comprehensive plan for monitoring and evaluating its performance.

From the start, the ATP has strongly embraced program evaluation and considers it critical to the development and operation of a results-oriented, efficiently run program. Early on, an evaluation plan was developed and measurable goals were identified against which to track performance.

ATP Competitions

The ATP conducts competitions each year to select R&D projects for support. Only project proposals submitted in response to a formal competition are considered. (Competitions are announced in the *Federal Register*, in *Commerce Business Daily*, and by direct mail, among other channels.)

Projects are evaluated against a list of criteria, including:

- the scientific and technical merit of the proposal,
- the potential for broad-based economic benefits to the United States,
- the quality of the proposer's plans for eventual commercialization of the technology—the ATP does not fund product development, but the proposer should have plans for capitalizing on a successful project,
- the level of commitment of the proposer and the adequacy of their organizational structure, and
- the experience and qualifications of the proposer.

Since 1994, the bulk of ATP funding has been applied to focused program areas—multiyear efforts of approximately $20 million to

$50 million per year, targeted at specific, well-defined technology and business goals. Often, these involve the parallel development of a suite of interlocking R&D projects. By managing *groups* of projects that complement and reinforce each other, the ATP can have the greatest possible impact on technology and the economy.

In addition to focused program competitions, which are open only to projects relevant to the program topic, the ATP sponsors at least one "general" competition each year, open to all technology areas. Past general competition awards have covered a broad spectrum of technologies in agriculture, biotechnology, microelectronics and electronics manufacturing, machine tools, advanced automotive manufacturing, advanced materials, information and communication technology, chemical processing, and other areas.

Regardless of whether a project is selected as part of a program or a general competition, awards to individual companies are limited to $2 million over 3 years and can be used only for direct R&D costs. Awards to joint ventures can be for up to 5 years, and joint ventures must provide more than 50 percent of the resources for the project.

Industry Input

The process of selecting program areas to focus ATP support is critical to success. Ideas for possible focused program areas come in from all sources, but particularly from industry: individual companies, trade associations, and professional societies. Universities and federal laboratories also have submitted "white papers" proposing possible ATP program areas.

Setting research priorities is a constant, ongoing process, beginning with submission of a program idea. If there appears to be sufficient industry interest in a particular program, the ATP generally hosts a public workshop to discuss and further refine the program concept. Other mechanisms for getting industry's input include:

- advice from senior industry technical and business managers;
- input from industry associations, trade groups, and professional societies; and
- analysis of proposals submitted to ATP in previous competitions.

Since every program has a fixed lifespan, there will be a constant turnover of programs as some are completed and others started.

"PROJECTS" VS. "PROGRAMS"

Make sure you understand the distinction between an ATP *project* and an ATP *program*!

An ATP Program:

- describes a major research direction for the ATP, with technology and business goals that generally involve a broad range of specific technology development tasks;
- may be proposed to the ATP at any time;
- involves multiple projects by single companies and joint ventures;
- provides a framework for one or more ATP competitions to solicit project proposals in support of the program goals—programs are not funded, projects are;
- involves no legal agreements between the proposer(s) and the ATP; and
- involves no proprietary information.

An ATP Project:

- is a specific research project;
- is proposed *only* in response to a formal ATP competition;
- receives ATP funds;
- involves a legal agreement between the proposer(s) and the ATP; and
- generally involves sharing proprietary information (which is legally protected from disclosure) with the ATP.

Each idea for a focused program is evaluated against four key criteria:

- the potential for a significant impact on the U.S. economy, including the credibility of the program's proposed pathways to economic growth, the importance of the existing or potential sector(s) affected, and the probability of subsequent commercialization;
- good technical ideas that are "cutting edge," high-risk, strategically important, and based on sound scientific and technical concepts;
- a strong industry commitment to participate, including breadth and depth of interest and willingness to share costs and to work with the ATP and other partners; and

- an opportunity for the ATP to make a major difference by supporting work that is unique or complementary to other industrial and government efforts, that offers timely and significant acceleration of research progress, and that requires a critical mass of funding that the ATP can provide.

Economic Returns

Early results indicate that the ATP is successfully improving the capability of the nation's businesses to capture economic returns from scientific and technological innovations. Two independent studies of projects funded in FY 1991 revealed substantial, early beneficial impacts on participating companies, including:

- expanded R&D activity, particularly the ability to engage in high-risk, long-term research with high-payoff potential;
- cost and time savings, improved productivity, and other benefits from industry-industry, industry-government, and industry-university collaborations;
- improved competitive standing;
- formation of valuable strategic business alliances;
- improved ability to attract investors;
- assistance in converting from defense to commercial applications; and
- acceleration of technology development, leading to improved market share.

Additional independent studies of the results of early ATP projects are under way.

New Strategies

Since FY 1994, the ATP has worked to reinforce its impact on the U.S. economy with several new strategies:

The ATP is taking a more active role in building cooperative programs among businesses, universities, and government agencies. Because of its global view and broad sources of information, the ATP is in a unique position to spot potentially advantageous alliances and bring them to the attention of its industrial partners. For example, the ATP might bring to the attention of a joint venture an outside company whose proposed work appears to mesh well with that of the joint venture. Or the ATP might suggest a strategic alliance between a single-company applicant proposing to develop a new technology and a potential end user of that technology, if such an alliance would increase the chances of a project's success.

Although the final decisions about such alliances will always lie with the companies, recognizing such opportunities gives the program an additional tool to increase the chances of success for its projects and to exploit promising opportunities that emerge.

The ATP will assist interested companies in planning for future commercialization and in developing linkages with investors. Many of the companies participating in the ATP—particularly small companies—are stronger in their R&D planning and implementation of the R&D plan than they are in their business planning and implementation of that plan. The early-stage, preliminary business plans developed by these companies often lack sufficient detail to provide the clear path to commercialization required by the ATP and may jeopardize many highly promising projects. The ATP will contract with private firms to provide business development support to ATP-funded companies that need such assistance.

The commercialization assistance program will be run initially on a trial basis. Several awardees have expressed interest in working with the pilot program. Its performance will be monitored and evaluated, and, if successful, it will be continued and expanded to serve all companies that wish to participate.

The ATP is intensifying its outreach efforts. While most of the larger technology-oriented companies in the United States are familiar with the ATP, the program is less well known or understood by thousands of small, entrepreneurial companies that play a critical role in technology development and might benefit from its programs. To remedy this, an intensified outreach program has been started to increase awareness of the program. The outreach program will be coordinated closely with state and local economic development organizations that are in a good position to identify small companies that might have an interest in the ATP.

Planning for success. President Clinton has proposed major increases in ATP funding to increase the number of awards made each year and the breadth of cutting-edge technologies covered. The expansion will allow the program to have a truly national impact on economic growth. The program's ultimate success will depend on an expanding relationship with U.S. industry to ensure a steady supply of good technical ideas and willing research partners to transform those ideas into successful new technologies with ATP support.

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October 1994

NIST

Advanced Technology Program

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Technology Administration
U.S. Department of Commerce

CRITERIA FOR ATP PROGRAM SELECTION

1. POTENTIAL U.S. ECONOMIC BENEFIT
   - A. Credibility of Proposed Pathways to Economic Growth
   - B. Importance of Affected Sectors
   - C. Probability of Subsequent Commercialization
2. GOOD TECHNICAL IDEAS
3. STRONG INDUSTRY COMMITMENT
4. OPPORTUNITY FOR ATP FUNDING TO MAKE A MAJOR DIFFERENCE

1. POTENTIAL ECONOMIC BENEFIT FROM THE PROGRAM

A. Credibility of Proposed Pathways to Economic Growth

B. Importance of Existing or Potential Sectors Affected

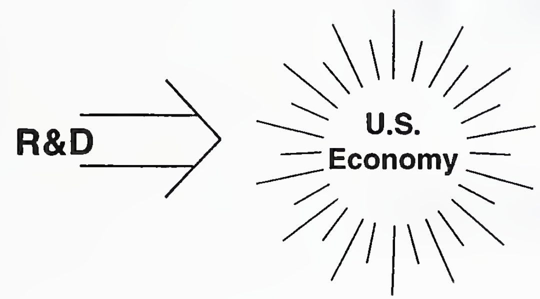
C. Probability of Subsequent Commercialization

A. CREDIBILITY OF PROPOSED PATHWAYS TO ECONOMIC GROWTH

- R&D Program directed towards economic goals?
- Research and business strategies properly integrated?
- Viable resource allocation plan?
- Pathways for implementation with workforce?

IS YOUR R&D PROGRAM DIRECTED TOWARDS ECONOMIC GOALS?

What problem are you trying to solve
or
opportunity to exploit?



VIABLE RESOURCE ALLOCATION PLAN?

Land, facilities, equipment, raw materials, human resources

- **Requirements?**
- **Current capacities?**
- **Strategies**

B. HOW IMPORTANT TO U.S. ECONOMIC GROWTH ARE THE AFFECTED SECTORS?

– How large

– How strategic

C. WHAT IS THE PROBABILITY OF SUBSEQUENT COMMERCIALIZATION?

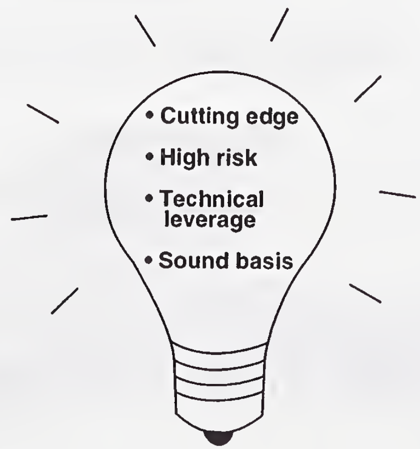
– Evidence that industry is committed to make it happen?

– Will nontechnical barriers be overcome? How?

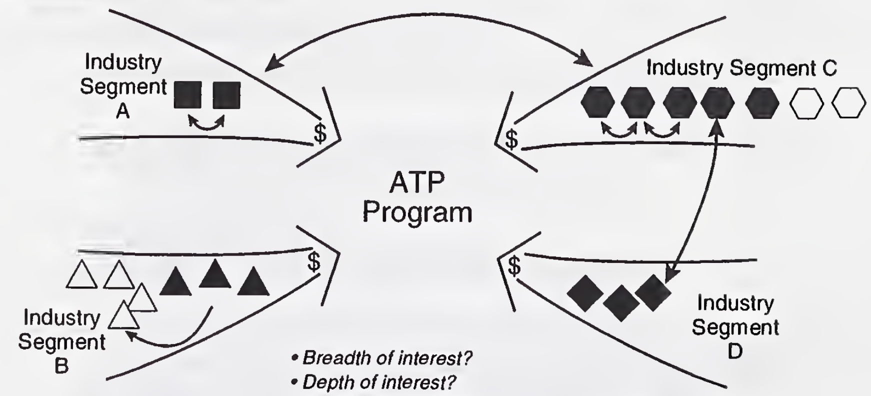
– Is the technology's advantage strong enough to drive commercialization?

– What are the threats / opportunities in the global marketplace?

2. GOOD TECHNICAL IDEAS

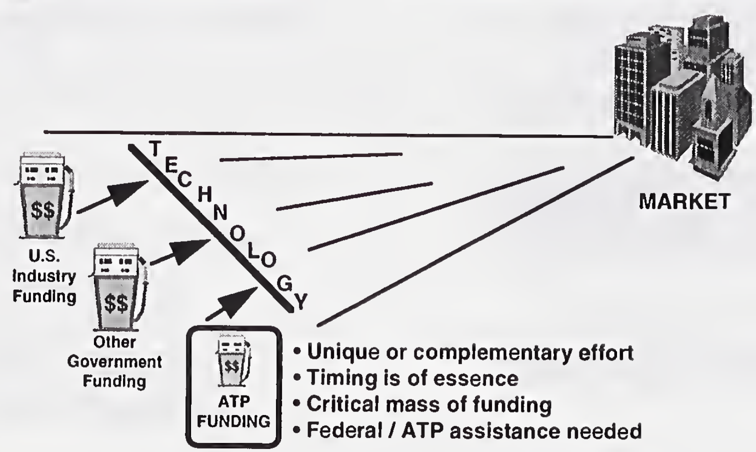


3. STRONG INDUSTRY INTEREST IN PARTICIPATING IN YOUR RECOMMENDED PROGRAM



- *Breadth of interest?*
- *Depth of interest?*
- *Ready to partner?*
- *Adequate vertical & horizontal linkages?*
- *Willing to cost share?*

4. WILL ATP MAKE A MAJOR DIFFERENCE?



- Unique or complementary effort
- Timing is of essence
- Critical mass of funding
- Federal / ATP assistance needed

Optoelectronics 2000 - A Proposed ATP Focussed Program

OPTOELECTRONICS 2000

Advanced Technology Program, ATP - National Institute of Standards & Technology, NIST

The rate of technology change is faster than it has ever been, and new markets spawning new technologies are emerging on the landscape daily. Optoelectronics currently enables products and services close to $80 billion of the near $1 trillion electronics industry. But what does the future bring? Where are the new markets? What are the new and emerging technologies that will fuel these markets? Who will be the players? Will U.S. industry lead or follow?

The answers to these questions and others are the focus of a new program under development at ATP - ***Optoelectronics 2000***. The scope of the program may include: optoelectronic materials, systems integration of optoelectronics, low cost packaging, high-volume optoelectronics manufacturing, and optical communications. We are seeking inputs to develop the scope of the ATP Focused Program in the form of a ***white paper***. The suggested format for the white paper is:

- Five to six pages; **no proprietary information**
- Describe the future markets in terms of monetary size and customers
- The technologies required to foster these new markets & technology costs
- The gaps to getting to these new technologies
- The amount industry is willing to cost-share with ATP for a focused program in optoelectronics

For more information, contact **Vic McCrary, 301-975-4321**, e-mail: vmccrary@nist.gov, or **Tom Lettieri, 301-975-3496**, e-mail: tlettieri@nist.gov. *This is your **chance** to shape a program that can catalyze new technologies and spawn new markets for the U.S. Optoelectronics Industry*! (See us also on the World Wide Web under "Electronics & Photonics"; **http://www.atp.nist.gov**)

Optoelectronics 2000: New Directions & New Challenges for the Optoelectronics - Semiconductor Industry

Advanced Technology Program

National Institute of Standards & Technology - NIST

Gaithersburg, Maryland 20899

Optoelectronics 2000

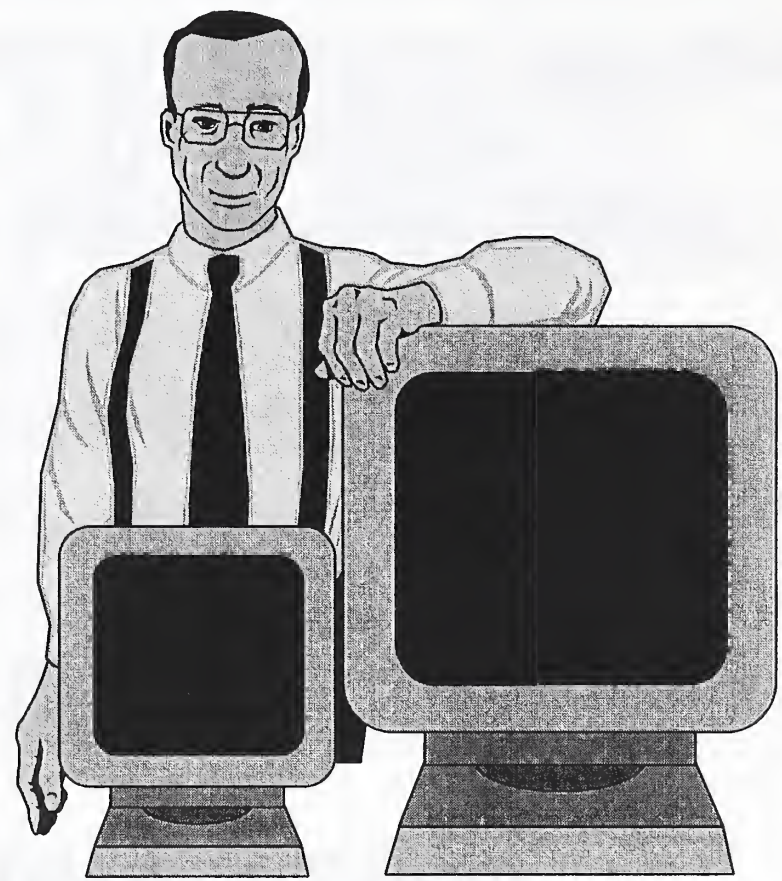
optoelectronics - "the interaction of light in with matter and the materials, devices & systems which depend on these interactions"*

Examples: lasers, LEDs, fiber, displays, switches, telephony, CATV, data storage, multimedia

* expanded from *Optoelectronics* by Wilson & Hawkes, 1989

Optoelectronics 2000: What is it?

- Assessment of the U.S. O/E industry, seeking the best areas where ATP funding can make a difference for the future
- Markets that drive new technologies
- Site visits; face-to-face with our customers



Optoelectronics 2000

"As technologies and industries converge, what is emerging is a new 'global information industry'. The new marketplace will no longer be divided along current sectoral lines. There may not be *cable* companies or *phone* companies or *computer* companies, as such.... There will be information conduits, information providers, information appliances, and information consumers."

U.S. Vice-President Al Gore

Optoelectronics 2000: '94 Information Market - $1.5 trillion

❖ Equipment	❖ **$150 billion / 9%***
❖ Communications Services	❖ **$750 billion / 7%**
❖ Products & Systems	❖ **$400 billion / 7%**
❖ Integrated Solutions	❖ **$100 billion / 12%**
❖ Content / Content Hosting	❖ **$50 billion / 12%**

* annual growth rate

Optoelectronics 2000: The Players - for now!

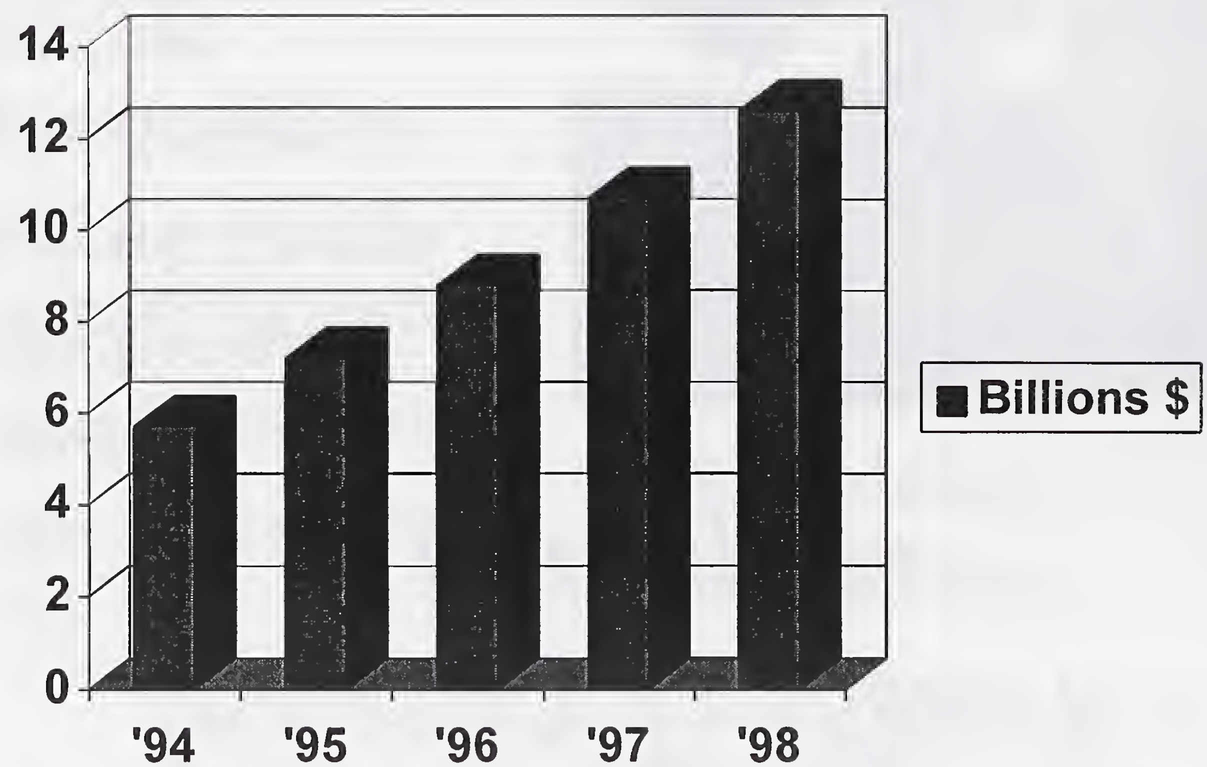
❖ Equipment	Alcatel, NEC, Bell Labs*
❖ Communications Services	MCI-BT, Telcos, MSOs, AT&T
❖ Products & Systems	NTT, Sprint
❖ Integrated Solutions	IBM, Motorola, Sony
❖ Content / Content Hosting	EDS, Andersen
	Microsoft, Sony
	TimeWarner,
	Matsushita

* proposed new name of AT&T equipment company

Optoelectronics 2000: Industry Feedback - Examples

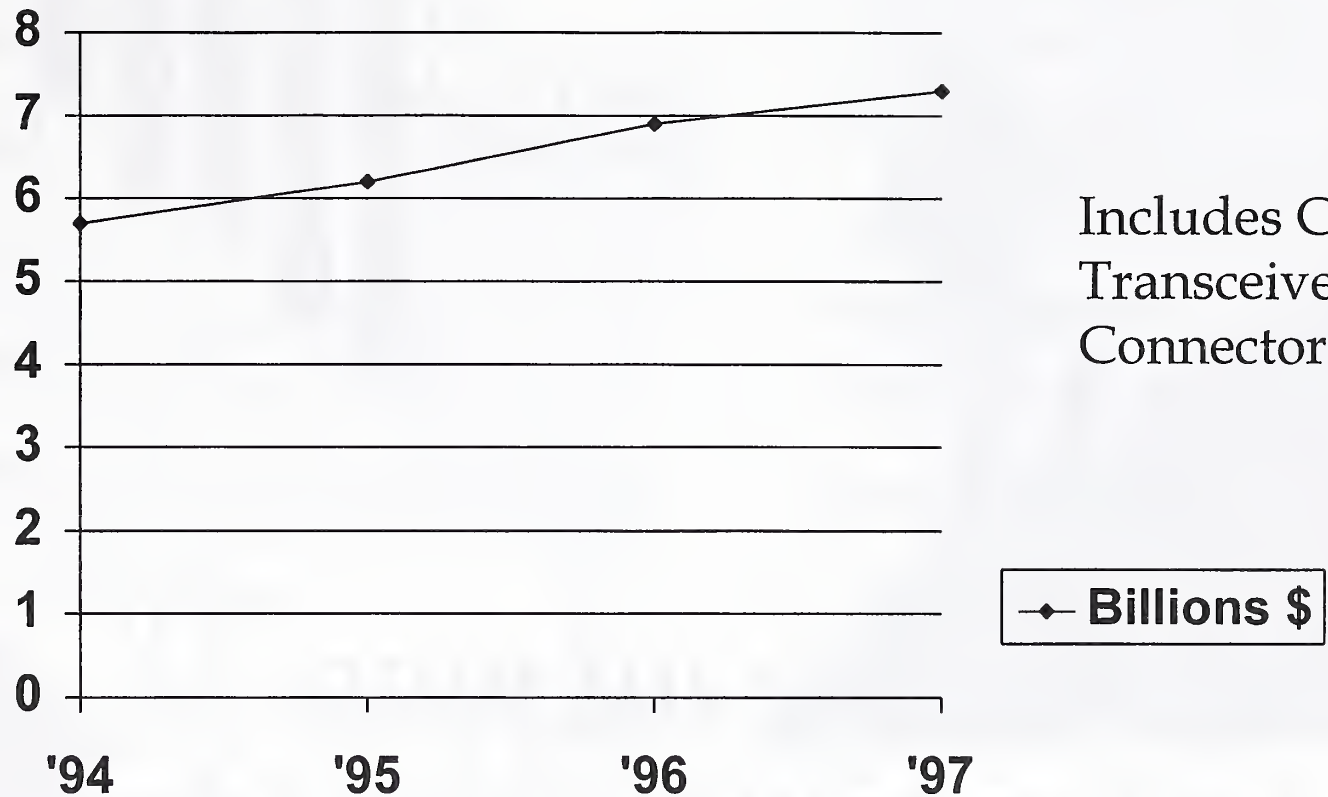
- Low-cost manufacturing
- O/E circuit design
- Systems design & architecture
- Software-to-system integration

Optoelectronics 2000: Consumer Spending on Interactive Technologies



Source: Workgroup Strategic

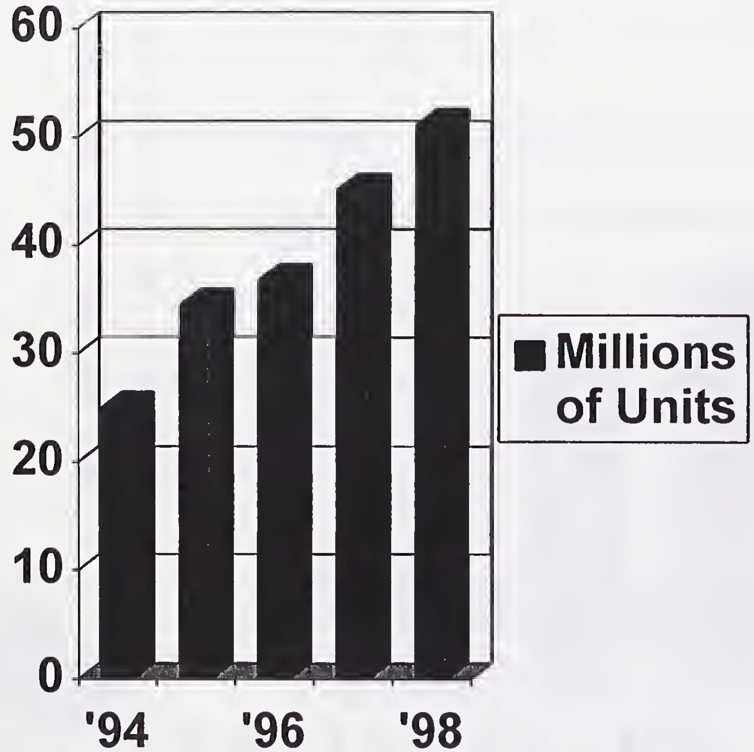
Optoelectronics 2000: Worldwide Fiber Optics Equipment Market



Includes Cable, Transceivers, and Connectors

Source: Data Communications

Optoelectronics 2000: PCs Sold for Networks



Source: Suhler & Associates

Networks are growing fast as companies replace old mainframe computers. "Connectivity, connectivity, connectivity" is the new business paradigm for success

Optoelectronics 2000: Challenges for the O/E Industry

- Manufacturing scale-up issues
- Materials
- Packaging & Assembly
- Fiber Connectors & Couplers
- Need to talk to each other!

Optoelectronics 2000

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Optoelectronics 2000

View us also on the
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From the ATP homepage, navigate to the "Electronics & Photonics" homepage.

III. Invited White Papers

OIDA OPTOELECTRONICS INDUSTRY DEVELOPMENT ASSOCIATION

Optoelectronics Technology Program Ideas

Proposal to the Advanced Technology Program,
National Institute for Standards and Technology

December 14, 1993

Optoelectronics Technology Program

This paper proposes ideas for an optoelectronics R&D program for the Advanced Technology Program (ATP) at the National Institutes of Standards and Technology. It describes the goals of the proposed program, the technologies to be developed, and the new industrial capabilities to be achieved. It discusses how this is to be done, and how these goals address the four ATP criteria.

Goal of Proposed Program

The goal of the proposed program is to accelerate the development and commercialization of optoelectronics technologies by leveraging increased industrial efforts in the areas that are most critical to the competitiveness of domestic industry. Optoelectronic technologies are key enabling technologies for the information age. They are essential for collecting, moving, storing, and displaying high volumes of information, and are essential for realizing the Administration's vision of giving everyone access to voice, data, and video information, anytime and anywhere. These technologies are becoming increasingly critical for both manufacturing and service industries. Domestic strength in the underlying technologies is essential for the United States to capture many of the jobs and economic benefits from developing the information infrastructure and producing the information appliances that make use of the infrastructure.

The proposed program focuses on the areas identified by industry as having the greatest economic impact over the next 5-10 years and are not the primary focus of other major Federal programs. These areas are primarily concerned with lowering the cost of technologies for high bandwidth communication (at intra-computer to intercontinental distances), high volume information storage, and information collection. The expected result of the proposed program is increased U.S. investment in key optoelectronic technologies, leading to faster commercialization, lower cost production, and a more competitive U.S. industry.

Optoelectronic technologies are also vital for flat panel displays and for advanced communication network architectures but because significant ARPA and DOE programs are focused on these areas, they are not the focus of this proposal. OIDA supports additional work in these areas, coordinated as appropriate with existing programs.

Technologies to be developed

The technologies to be developed in this program are devices, systems, and supporting infrastructure that will help lower the cost of optoelectronics. Specific topics are infrastructure base technologies, optical storage, hybrid optoelectronic modules, prototype low cost optoelectronic network systems, machine vision, and tunable lasers for wavelength division multiplex (WDM) networks and spectral sensing. The technologies suggested include some that are close to the market as well as others that represent longer term

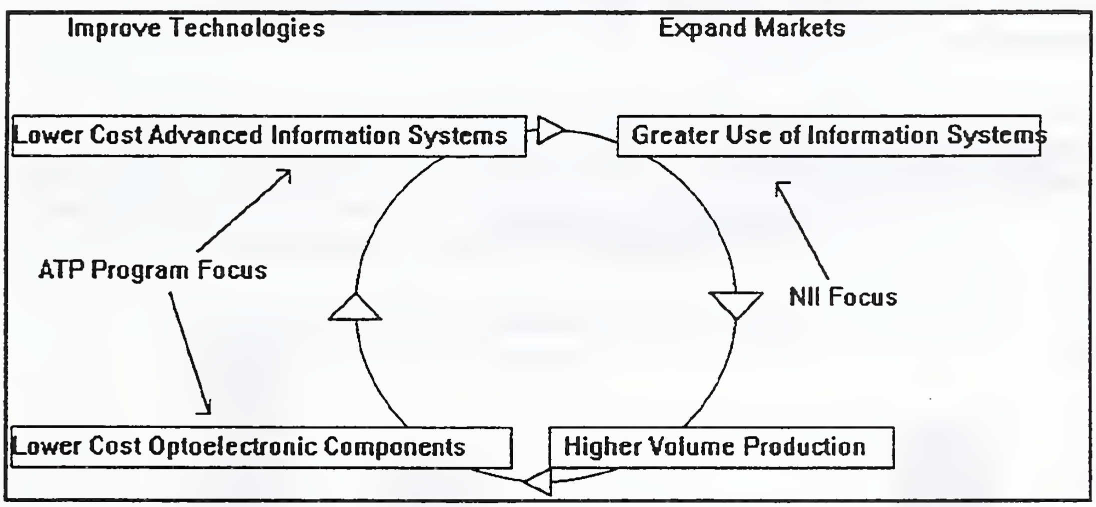
opportunities. Some of these technologies, such as machine vision and spectral sensing, might be equally well supported under an ATP program in manufacturing.

New Industrial Capabilities to be Achieved

The proposed program will give the United States a much more robust domestic industry in key information technologies. In particular, it will improve the competitiveness of the domestic industry in the high volume, mass market segments of the industry where the U.S. is relatively weak.

Although optoelectronic information systems can provide enormous benefits to the nation, commercialization of many technologies has been slower than is optimal. A main problem is that although low cost optoelectronics are necessary to bring down the cost of systems so they can be used in high volume applications, high volume production is necessary to bring down the cost of these technologies. The proposed program will help solve this problem by developing lower cost techniques for optoelectronics production, packaging and systems. This will accelerate the positive feedback loop shown in figure 1 below.

Figure 1



The proposed program is complementary to and supportive of efforts by the Administration to accelerate the development of the national information infrastructure through changes in regulatory policy and through demonstration projects. These programs will help expand the use of advanced information technologies by reducing regulatory impediments to investments and stimulating new markets.

How the Proposed Program Meets the ATP Criteria

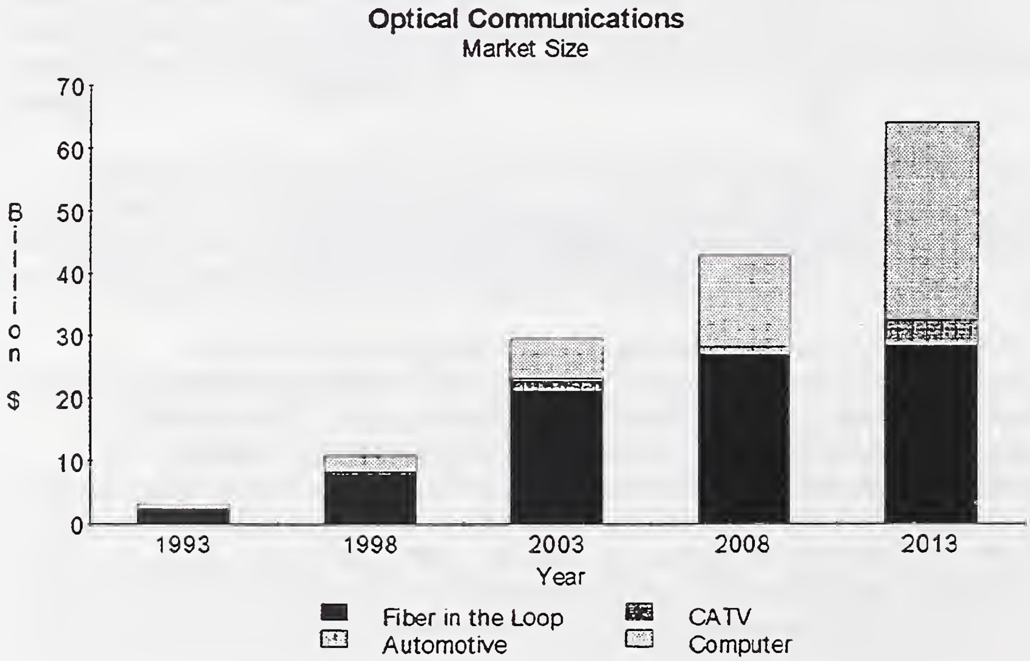
Potential for U.S. Economic Benefit

The proposed program will improve U.S. competitiveness in the large and growing industry that is based on optoelectronic technologies. It will also help to expand services based on optoelectronics, which will in turn provide many other economic and societal benefits.

The focus of the proposed program is derived from OIDA's Market Assessment and Technology Roadmap, a two-year effort by the North America optoelectronics industry to determine the areas where technical developments can have the greatest economic impact. Because the technical priorities that chosen are those that are most vital to the industry, the industry is ready to rapidly commercialize the results.

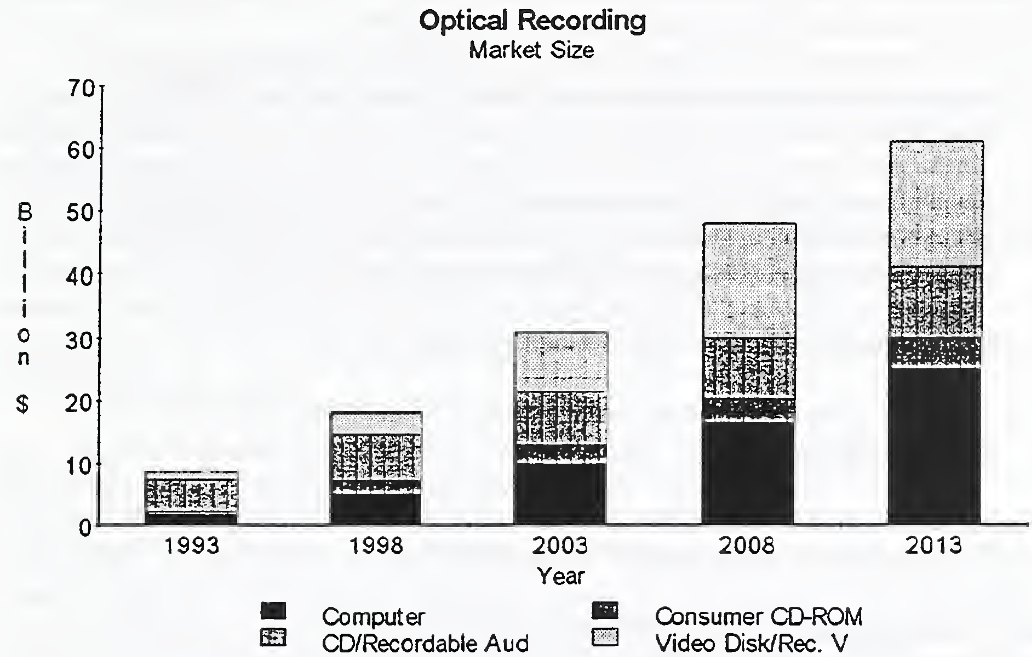
The OIDA, based on its market assessment project,[1] projects that the worldwide market for products enabled by optoelectronics will grow from $75 billion in 1993 to $463 billion by 2013. These figures are the markets for products at the highest level of integration for which optoelectronics are the enabling technology (e.g. compact disk players or automotive communications subassemblies). The spectacular growth comes from the increasing use of optoelectronics in electronic equipment as well as from the expanding market for electronics in general. This proposal will have an impact on major segments of this growing market.

The market for optoelectronic communications equipment, including applications in telecommunications, computing, cable television, and automobiles, is expected to grow to over $30 billion by the year 2003.



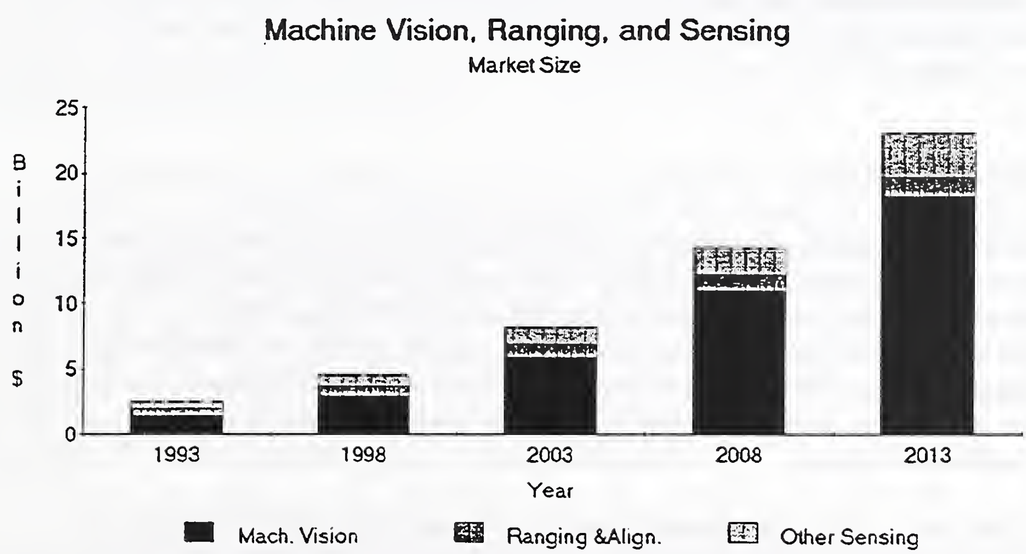
Source: OIDA

The market for optical storage equipment, including computing and consumer markets, is also expected to reach $30 billion by the year 2003.



Source: OIDA

In addition, there is a large market for optoelectronic-enabled systems in manufacturing. The markets for machine vision, ranging and alignment, and other sensing are expected to reach $8 billion in the next ten years. These technologies can also contribute to large improvements in manufacturing quality and productivity.



Source: OIDA

These figures do not include the value of services enabled by optoelectronics, which is much larger. Although estimates are somewhat speculative, the Administration's Information Infrastructure Task Force report,[2] cites estimates that the NII will add $190 billion to over $300 billion to the GDP. Examples of the benefits are:

- Improved education, through distance learning and interactive computer-based video instruction.

- Reduced energy consumption and pollution through telecommuting and teleconferencing. A 20 percent substitution of communications for personal transportation would result in $23 billion in annual energy savings.

- Reduced loads on power plants through telemetering.

- Increased efficiency in manufacturing through wide area computer aided design and manufacturing.

- Reduced health care costs through better management of patient records and claims, and better communication among physicians.

Many of these benefits would be enhanced by faster and greater use of optoelectronics that would be developed in this proposed program.

The economic benefits from an ATP program in optoelectronics can be very large. For example, if a $50 million/year ATP program results in a 5 percent increase in the U.S. share of the year 2003 global market for optical communication and storage equipment, the result would be a $3 billion/year benefit to the U.S. economy, 60 times the annual ATP expenditure. If tax revenues capture 20% of this economic activity, revenues to the government would increase by $600 million/year, many times the Federal contribution to the program. Total benefits to the economy, through benefits to other sectors of the economy, would be much greater.

Good Technical Ideas

As a fast moving, emerging technology, there is no shortage of good technical ideas in optoelectronics. The challenge is to support the ideas that will have the largest economic impact, which often means making the good ideas practical and affordable. This is particularly true since much of the work in optoelectronics has been either defense-related or university-performed R&D, both of which have tended to focus on high performance applications with less regard to cost. The challenge now is to bring the costs down and to expand the market applications.

The following are some possible program ideas, ranging from development of individual devices, to establishment of infrastructure, to demonstration and insertion. They are largely based on technical priorities identified in OIDA's technology roadmap project,

and are thus programs that can leverage great benefits for industry. These ideas can serve as a starting point for further discussion. In each area, OIDA can assist to further define the areas by polling the industry and conducting workshops to achieve consensus and to develop systematic approaches.

Infrastructure Base Technology. This area includes the development of: passive alignment for discrete and array devices, standardized optical substrates, low cost precision package enclosures, passive planar and microoptics for optical chips, device arrays for wavelength division multiplexing, microlenses, adjustable precision micro-mounts, replicable holographic elements, miniature passive elements such as integratable polarizers and isolators, and molded plastic connectors and couplers. These components are analogous to those available for assembly of electronic modules. Overseas competitors have an advantage because the commercial camera industry has established an optics base for consumer products. An improved technology base would greatly expand U.S. applications development.

Hybrid Optoelectronic Modules. A typical high performance optoelectronic module will consist of dissimilar materials due to the demands to provide functions by devices that best use particular materials. For example, VLSI can best be done in Si, high speed electronics and optoelectronic transducers in III-V materials, waveguiding in SiO_2 or organic polymers, and non-linear properties in yet other exotic materials. Hybrid modules are also a necessary step if monolithically integrated OEICs are to be achieved. This program would demonstrate manufacturing with compatible integrating processes and will incorporate novel test paradigms to contain costs at low throughput.

Prototype optoelectronic network systems Using plastic and/or fat fibers and standardized transceivers, this programs would develop a family of affordable, user friendly, easy to install, optoelectronic modules that would create value added leverage in the manufacturing sector for real-time, on-line, non-interfering monitoring and control by transferring high speed data and high resolution images. The low cost and safety features will also extend the technology to home use, such as fiber to the home. The goal is to develop packages with cost of $0.1 per Mb/s for applications spanning low bit rates (25Mb/s) to high bit rates (>1000 Mb/s).

Optical Storage The focus here would be to accelerate the development of blue laser diodes. If a semiconductor, injection laser diode can be manufactured with long life and reliability, optical recording will be extended to small systems suitable for personal use. The United States had a small lead by achieving the first lasing of a blue-green laser diode, but with a subsequently launched massive effort Japan has closed the gap and may have leaped ahead. Specific projects that might be included in this program are the development of a centralized facility for advanced engineering samples, development of manufacturing infrastructure for commercializing laser advances, and development of new plastic substrate technology for recording media and servo format fabrication.

Machine Vision An optical correlator using the principal of spatial frequency matching (Fourier Transform) is theoretically sound for pattern recognition. All the critical components have recently been developed, including semiconductor laser diodes with high

quality beam output, spatial light modulators with large number of pixels, and high speed CCD arrays. A compact, rugged, and affordable module incorporating electronic versatility and high optical throughput can be developed to aid manufacturing or assembling processes. A vertical integrated development team including end users could demonstrate insertion into an operational system. Although a general automatic target recognition (ATR) system may be extremely challenging, if sensible boundary conditions for particular operations are imposed, optical correlators are capable of errorless matching. For example, small numbers of objects constrained in orientation and size that satisfy the usual requirement for automated assembly lines are ideally suited to be controlled by machine vision of this nature.

Tunable Lasers for Wavelength Division Multiplex Networks and Spectral Sensing Lasers that are capable of rapid tuning onto repeatable wavelengths are critical elements for a WDM network. Arrays of lasers that can be tuned around prescribed wavelengths and can be operated with long term stability are the necessary enabling technology. The likely adoption of 1.54 micrometer as the operating wavelength indicates that indium phosphide based devices and components need to be developed for manufacturing to overcome the effects of low volume production.

The technique of spectral sensing is truly discriminating and versatile in detecting and differentiating atomic and molecular species. It can sense remotely and non-invasively, as is suitable for environmental surveillance. Its real-time capability enables on-line monitoring and control for manufacturing operations. The technology is not widely deployed because tunable lasers are expensive and difficult to use. New technological advances enable semiconductor tunable laser diodes with narrow linewidth. These lasers can be compact, affordable, easy to use, and span wide spectral ranges. This family of devices will promote widespread uses of spectral sensing in on-line monitoring and environmental surveillance.

As noted previously, OIDA also supports work in other areas, such as displays, optics in computing, and hard copy technologies, but has not included them in this proposal. If ATP is planning to work in these areas, OIDA would be pleased to participate.

Strong Industry Commitment

The existence of the OIDA is evidence that industry is committed to working cooperatively among itself and with government to develop the industry. OIDA members have already devoted time and funds to begin to develop the industry and are committed to working further. In addition, the high percentage of previous ATP awards in optoelectronics is evidence that industry is ready and willing to work with government. Industry is already committing substantial amounts of its own funds for R&D.[3]

We would expect the proposed program to support a mix of vertical and horizontal alliances. OIDA's membership already incorporates materials, devices, and systems companies, and all of these have been involved in developing OIDA's priorities. In optoelectronics, as with semiconductors, the primary Japanese advantage is in low cost, high volume production. The success of SEMATECH illustrates that it is possible for U.S.

companies to cooperate very effectively in improving manufacturing technologies to lower costs.

The Opportunity for ATP Funds to Make a Significant Difference.

Federal funding is essential for several reasons. First, international competition is intense and Japan leads in many areas. Because technical advances are rapid there are many opportunities for the U.S. to regain a strong position. Steep learning curves, however, mean that the companies and collectively the countries that get early leads can gain a sustainable advantage. Regaining a strong U.S. position will become increasingly difficult as time goes on.

A substantial part of the reason that the U.S. lags is that the investment environment for capital intensive technologies whose returns will be a number of years in the future has been consistently better in Japan than in the United States. For a variety of reasons that are beyond the scope of this paper, U.S. capital providers tend to demand higher rates of return and faster payback than do their overseas competitors.[4] The ATP program, through its cost sharing, can reduce the cost of long range technology investments to U.S. industry, and can significantly expand the long range R&D.

A second reason is that there are a large positive externalities or public goods associated with optoelectronic technologies. As noted above, the Administration supports developing the national information infrastructure because of the large potential benefits to many parts of society. Individual firms cannot capture all of the benefits for themselves, and therefore will by themselves underinvest in the underlying technologies.

A third argument for Federal involvement is that optoelectronic technologies are by nature revolutionary, and require changes that are beyond the scope of individual companies. Individual companies underinvest because their success in a particular technology depends on a large number of complementary investments in other technologies that are beyond their control.[5] There is a need for coordination, so that interdependent technologies needed for new systems are developed together. OIDA, through its market assessment and technology roadmap is beginning to provide this role, but a coherent ATP program would also help stimulate coordinated investment.

ATP support is particularly important because no other Federal programs have the same focus on improving industrial competitiveness. There are some complementary programs in the Department of Defense and the Department of Energy that have tended to focus on the high performance technologies that are important for the defense industry. OIDA will work cooperatively with these other groups and we expect that some ATP awards in this area would involve the Federal laboratories as partners to use their technical talent and facilities. OIDA is discussing areas of cooperation with several laboratories.

The amount of funding possible in an ATP program could have a very significant impact on the industry. $50 million, leveraged with industrial contributions to at least $100

million/year, would greatly increase the domestic investment in the key technology areas identified.

Conclusion

We believe the program ideas outlined here could make a significant contribution to the nation's economy. The Optoelectronics Industry Development Association is willing to work with you to refine and shape these ideas.

[1] Optoelectronics Industry Development Association, *Market Opportunities in Optoelectronics*, 1993. 211 p.

[2] Information Infrastructure Task Force, *National Information Infrastructure Task: Agenda for Action*, September 15, 1993.

[3] Preliminary drafts of a Department of Commerce Export Adminstration survey indicates substantial industrial R&D investment. This survey is expected to be released soon.

[4] See, for example, Council on Competitiveness, *Capital Choices: Changing the Way America Invests in Industry*, Washington, June 1992.

[5] See Sternberg, Ernest, *Photonic Technology and Industrial Policy: U.S. Responses to Technological Change*, Albany, NY, State University of New York Press, 1992.

Optoelectronic Technology Roadmap

Conclusions & Recommendations

OIDA *Optoelectronics Industry Development Association*

OIDA Membership

Voting Members:

AMP Inc.
AT&T
Bellcore
Bell-Northern Research
Corning, Inc.
Hewlett-Packard Company
Hughes/GM
IBM
Motorola, Inc.
NYNEX
3M

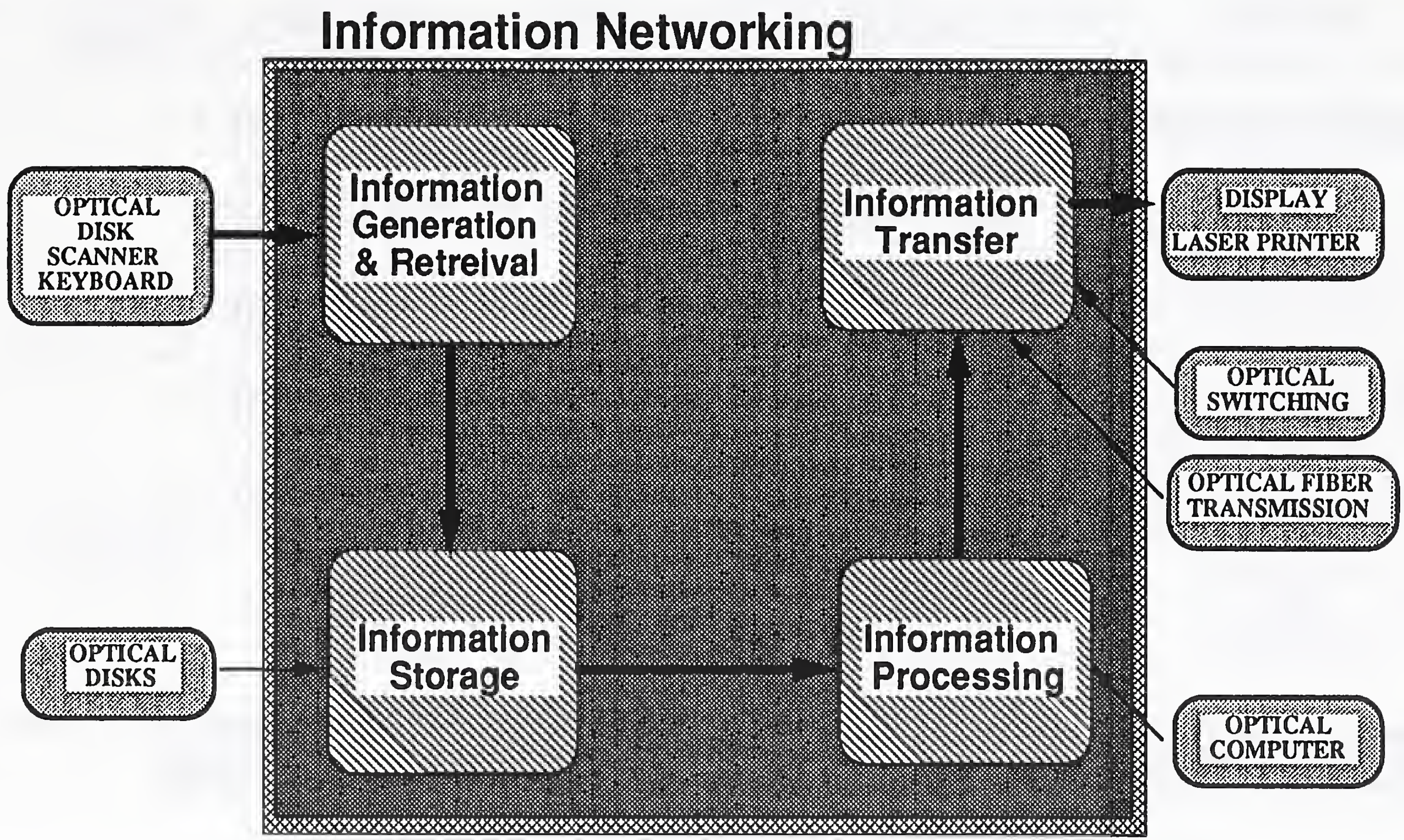
Associate Members:

Advanced Display Systems, Inc.
AstroPower, Inc.
Cree Research, Inc.
Digital Equipment Corporation
Honeywell/Microswitch
Lawrence Livermore National Laborarory
Martin-Marietta Corporation
National Research Council of Canada
National Optics Institute
Optex Corporation
Optivision, Inc.
Ortel Corporation
Page Automated Telecommunications Systems Inc.
Photonics Research Inc.
Planar Systems, Inc.
Polaroid Corporation
SDL, Inc.
SI Diamond Technology, Inc.
Three-Five Systems
United Technologies Research Center
Waterloo Scientific, Inc.

University Affiliate Members:

Center for Research & Education in Optics and Lasers, University of Central Florida
Center of Integrated Photonics Technology, USC
Optoelectronics Technology Center, UCSB
Optoelectronics Materials Center, University of New Mexico
Photonics Research Center, University of Connecticut

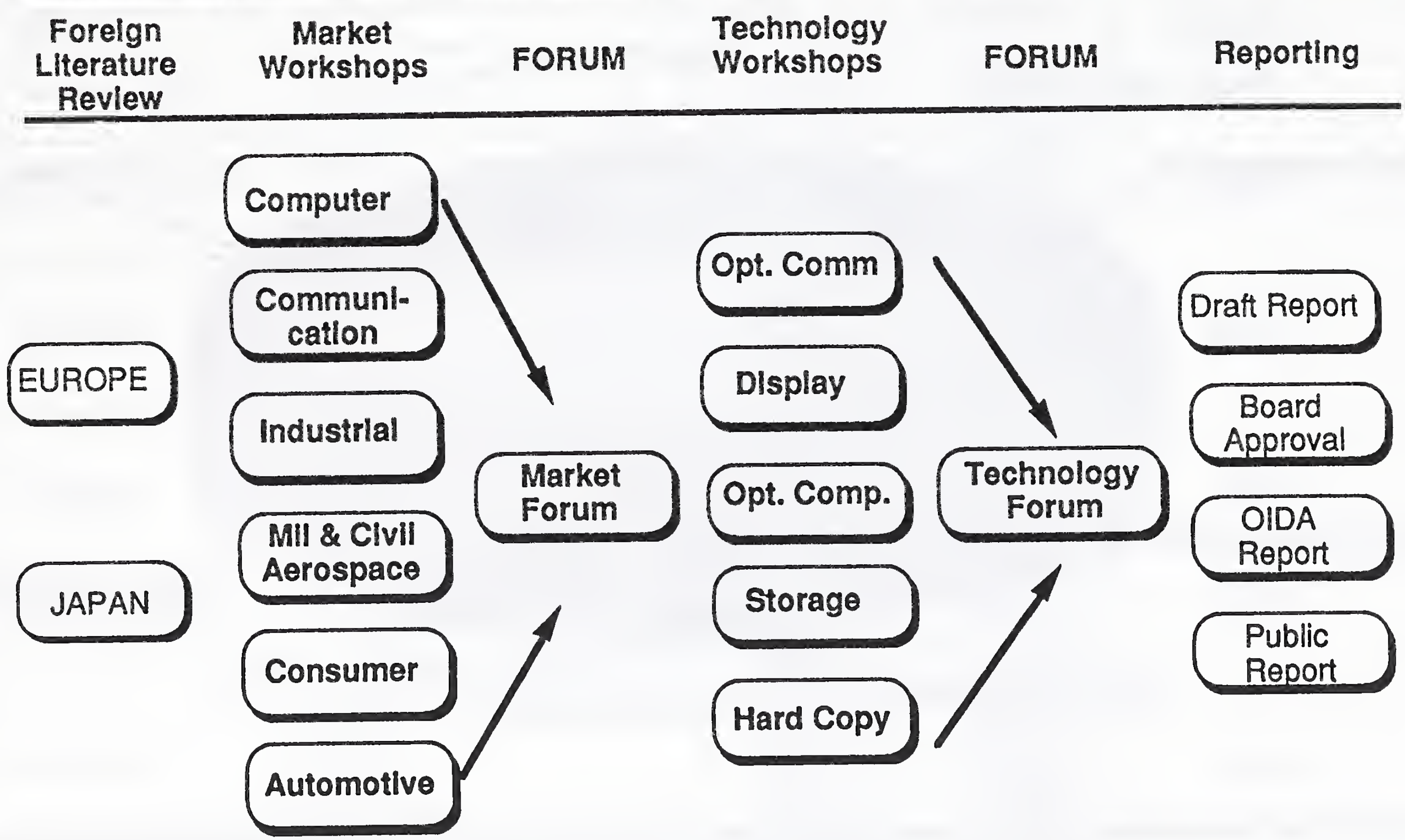
The Role of Optoelectronics in the Information Age Technologies



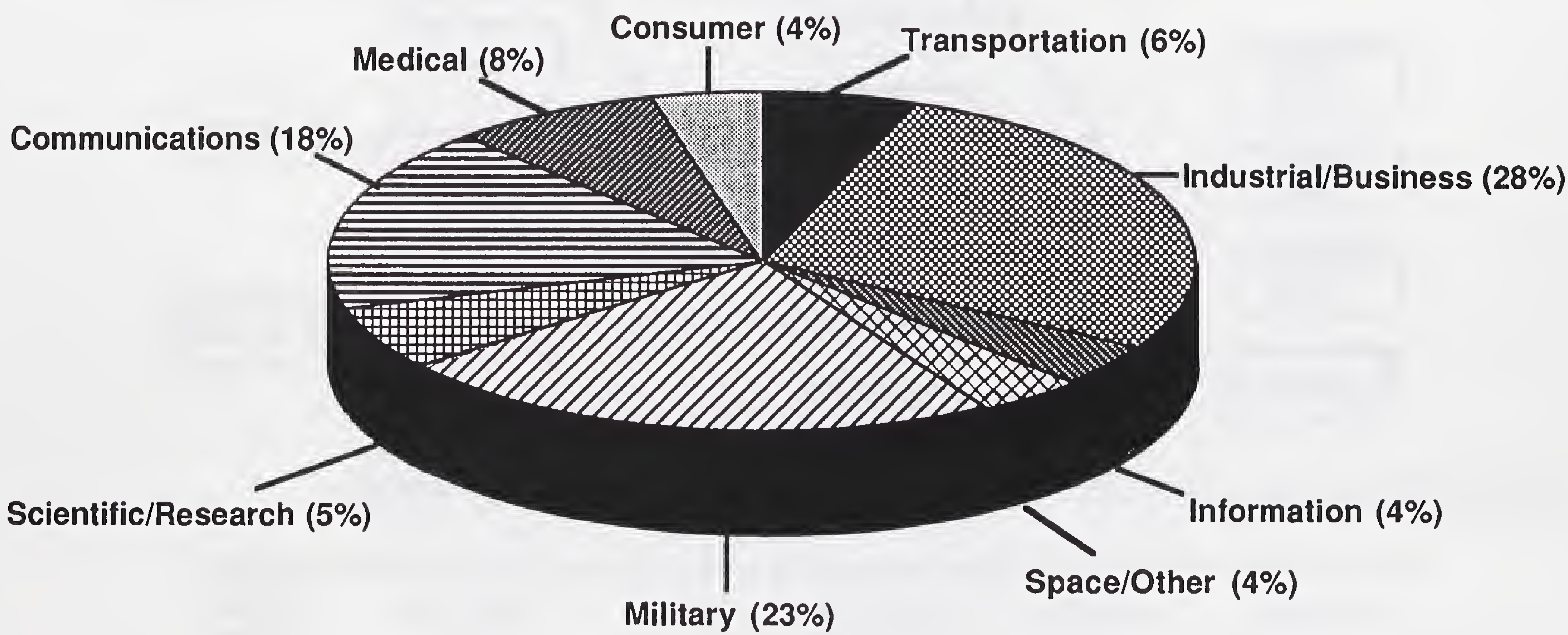
Why should ATP focus on Optoelectronics?

- Critical enabling technology
- Key technology for the Information Age
- Key technology for national defense
- Worldwide U.S. marketshare is low ~ 15%
- Major competititors are subsidized by their own government
- The U.S. OE industry is evolving
- Stand alone component suppliers have low profit margins

OIDA Market Research and Technology Roadmap



Markets for Optoelectronic Products (102 Establishments Reporting)



Source: BXA Optoelectronics Survey

OIDA

Relative Position of the North American OE Industry

Sector	Product	Components	Equipment	INDEX
Communications	Fiber-to-the-curb	even	strong	2.75
	CATV	strong	strong	
Industrial	Medical	strong	strong	2.50
	Production	weak	even	
	Energy conversion	strong	strong	
Automotive	Datacomm	even	strong	2.00
	Display	weak	even	
	Lighting	even	even	
	Sensors	even	even	
Computer	Optical memory	weak	weak	1.63
	Display	weak	even	
	Datacomm	even	strong	
	Printers	weak	even	
Military/Aerospace	Military	even	strong	2.50
	Civil aerospace	even	strong	
Consumer	CD & recordable audio	weak	weak	1.33
	Videodisk & recordable VD	weak	weak	
	CD-ROM	weak	weak	
	HDTV	weak	even	
	Videophone	weak	even	
	PDA	weak	strong	

Legend: weak — even — strong; ← North American Position

OIDA Ref. OIDA

Some of the most promising technologies

Manufacturing infrastructure

- Substrates
- Epi Reactors
- Alignment tools
- Packaging

Some of the most promising technologies - 2

Blue to /UV light sources

- Optical storage
- Hard copy
- Lighting / Displays

High resolution image sensors

- Digital photography
- Multimedia communication

Some of the most promising technologies - 3

Vertical cavity surface emitting laser arrays (VCSEL)

- Optical transmisssion
- Scanners
- Hard copy
- *Optical Interconnects*
- *Optical sensors*

Some of the most promising technologies - 4

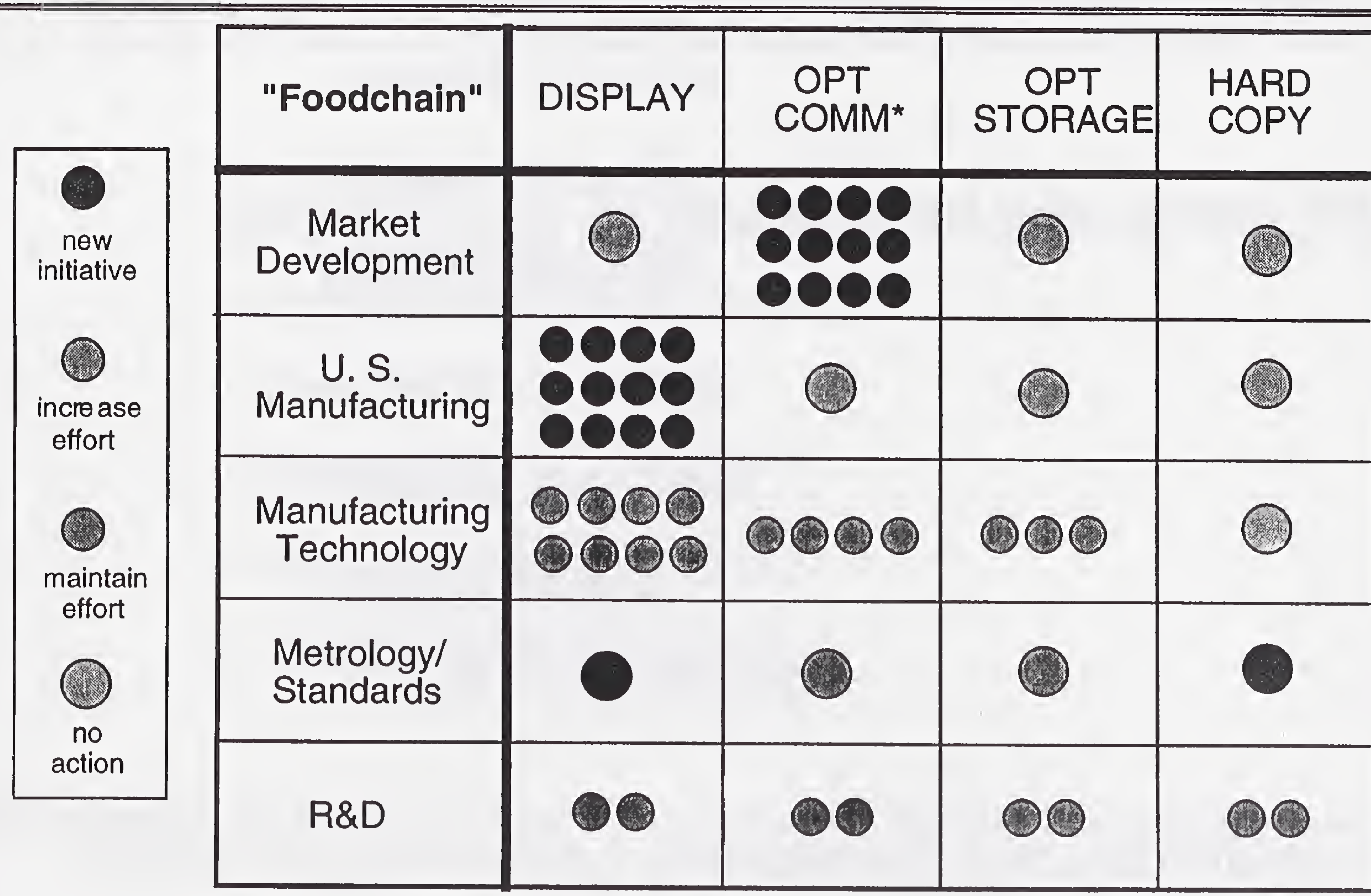
Optical Interconnects

- Laser arrays
- Hybrid mounting
- Detector arrays

Optical sensors

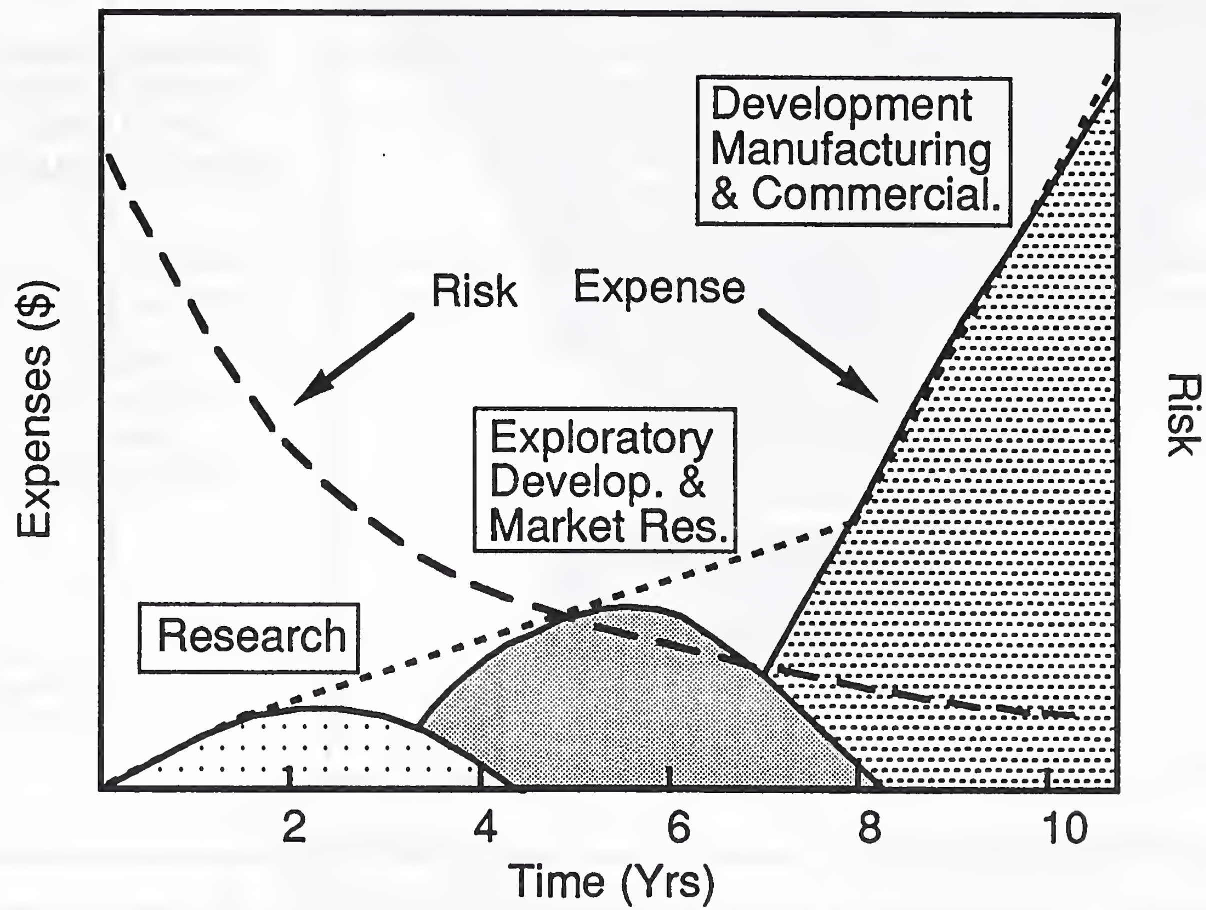
- Fiber sensors
- Image sensors
- Machine vision

Summary of OIDA Technology Roadmap Recommendations - 4/94

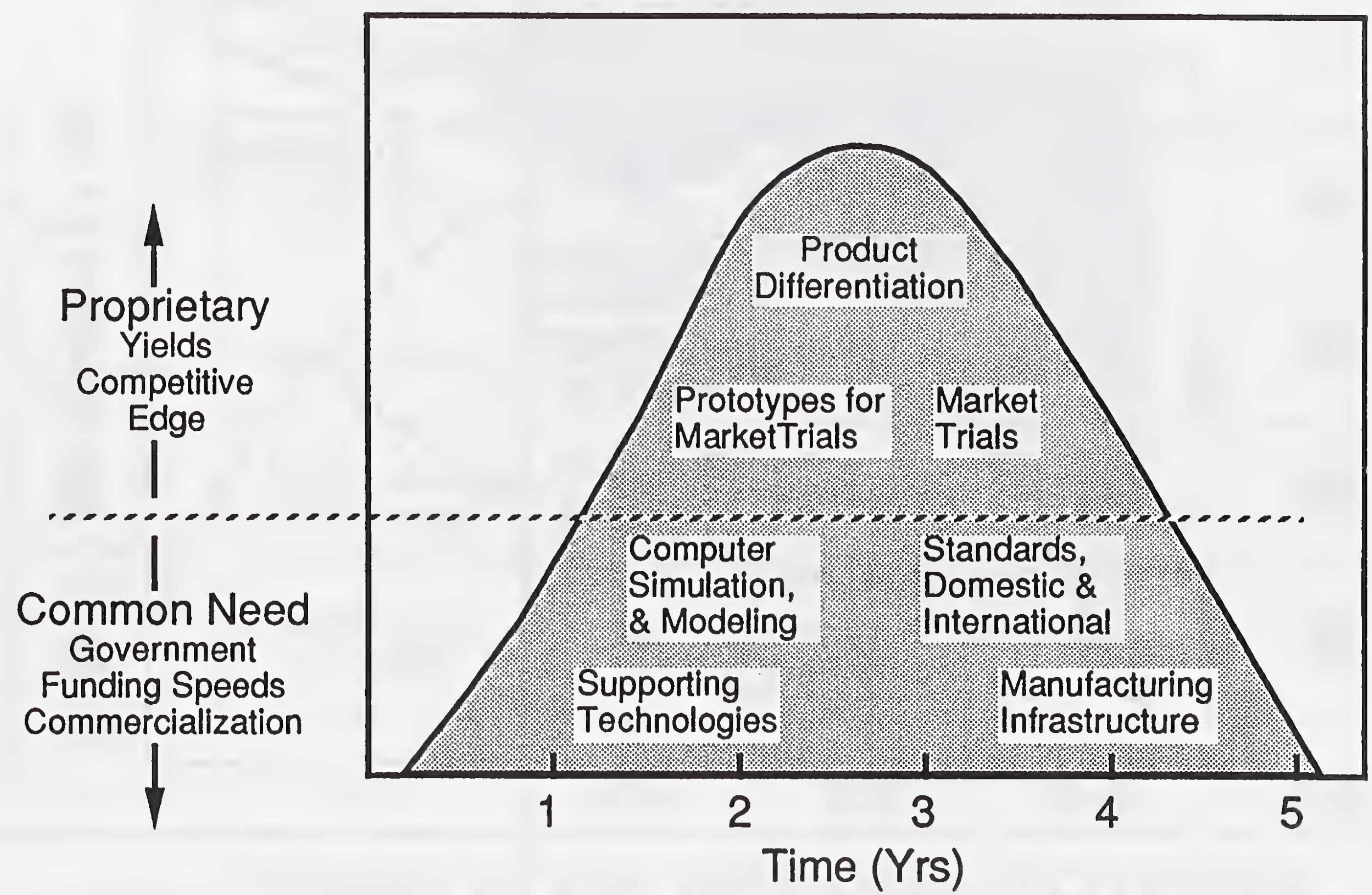


*Optical Communication includes telecommunication, data communications, and optical switching and computing

Three Phases of the Innovation Process

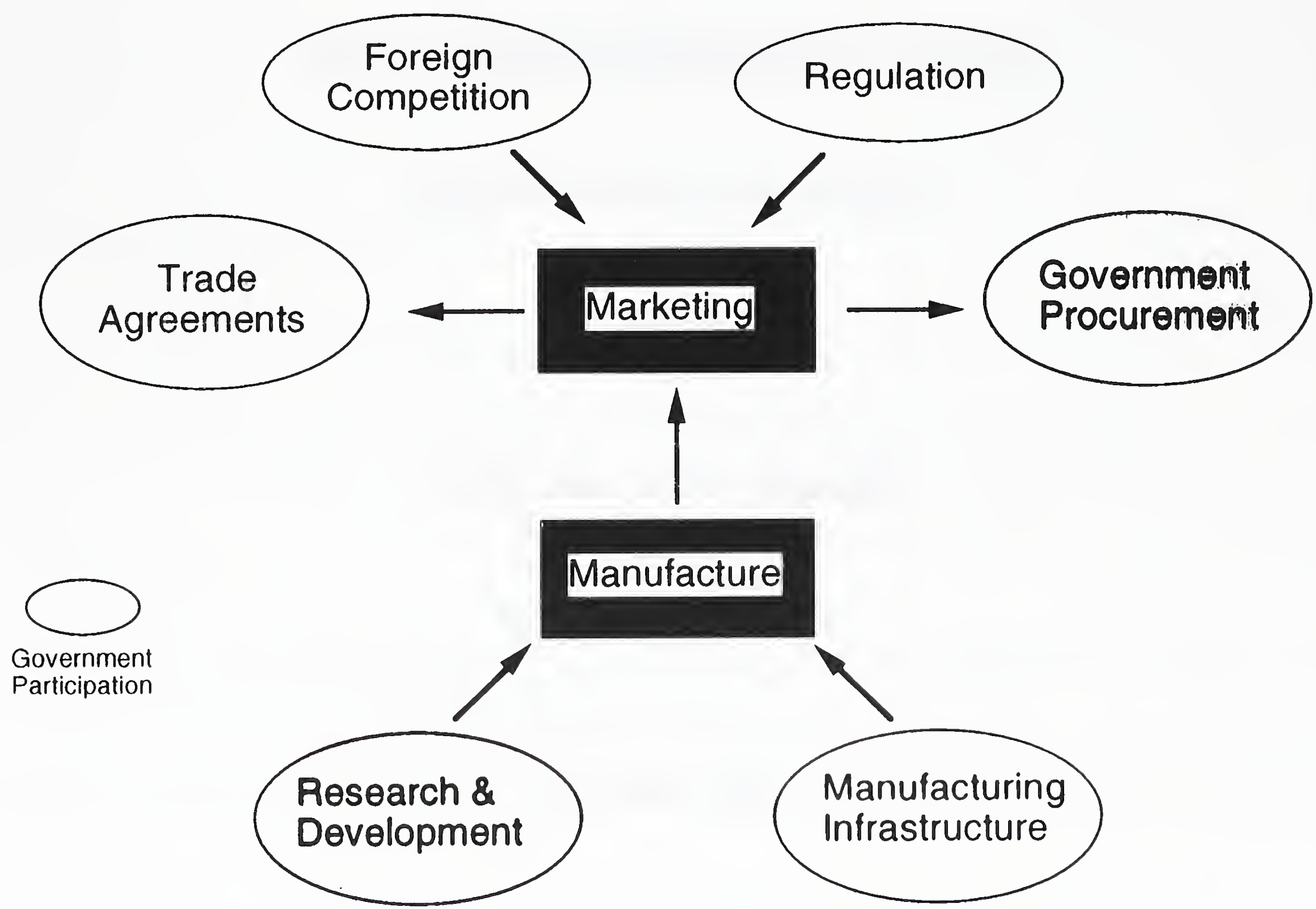


Exploratory Development and Market Research



OIDA

Forces in the Commercial Foodchain



National Electronics Manufacturing Initiative

Framework for the Technical Plan

Prepared by the
NEMI Industry Team

Bob Klaiber, AT&T, Chairman
Bob Pfahl, Motorola
Roger Pollak, IBM
Sam Wennberg, Delco

February, 1995

The National Electronics Manufacturing Initiative Plan

NEMI is a Government/Private Sector Partnership to improve U.S. competitiveness in manufacturing.

- Led by the U.S. Electronic Manufacturing Industry
- Clarifies and prioritizes existing government R&D programs in electronics (ARPA, NIST, etc.)
- Builds on U.S. strenghts in electronics

NEMI Objectives

- Improved Industrial Profitability
- Improved Industrial Global Competitiveness
- Providing High Quality Jobs in the U.S.
- Improving the U.S. World Trade Position
- Provide for National Defense
- Empower U.S. Citizens in Business, Education, Health Care

The NEMI Focus

- Electronic Hardware that Connects to the National Information Infrastructure (NII)
  - hardware used to Sense, Store, Process or Communicate Information
  - Includes wireless terminals, PCs, optical transceivers, modems, NIU
- The Broad Area of Concentration will be Assembly and Packaging

NEMI DRIVERS

- The U.S. Electronics trade deficit increased from \$3.9B in 1990 to \$17.2B in 1993
- The U.S. now has a trade deficit in computer hardware amounting to \$8B in 1993.
- Patents issued to Americans for Electronics and Communications equipment is steadily dropping, currently at 48%
- Japan leads the world in low-cost electronics packaging and miniaturization, except for flip-chip processes and design
- **Low-cost opto-electronics will play an important role in the delivery of multi-media services, yet the U.S. is significantly weaker than Japan in this key technology**
- Electronics is a key multiplier in many industries, impacting automobiles (20%) and most other businesses
- At current rates, the U.S. will miss out on much of the \$2 trillion global electronics market in 2000
- There will be an adverse impact on employment in the electronics industry if these trends are not reversed.

NEMI
Schedule of Activities

May-Sept, 1994	NEMI Framework Committee generates technology options and extensive roadmaps
Nov. 1994	Version 4.0 of NEMI Options/Roadmaps issued
Nov. 16, 1994	NEMI Industry Leadership Group meets to chart a technical plan and organization structure. An industry team is formed to generate a detailed technical plan
Nov. 1994-Mar 1995	NEMI Industry Team develops product vision, technical plan and roadmaps for NEMI
March 23, 1995	Industry Team present plan to the Leadership Group

Organizational Composition of the NEMI Leadership Group

Adept Technology
AEA
AMPEC
ARPA
AT&T
Brigham Young Univ.
Dover Technologies
EIA
HADCO
Hewlett-Packard
Hughes/Delco
IBM
IEEE
Intel
IPC, Inc.
Lawrence Livermore Labs
3M
MIT
Motorola
MPM Corp
Pensar Corp
Sandia
Scheldahl
Solectron
Systems Planning Corp
Texas Instruments
Trimble Navigation
Universal Instruments
Univ. of California
Xerox

NEMI
Areas of Concentration

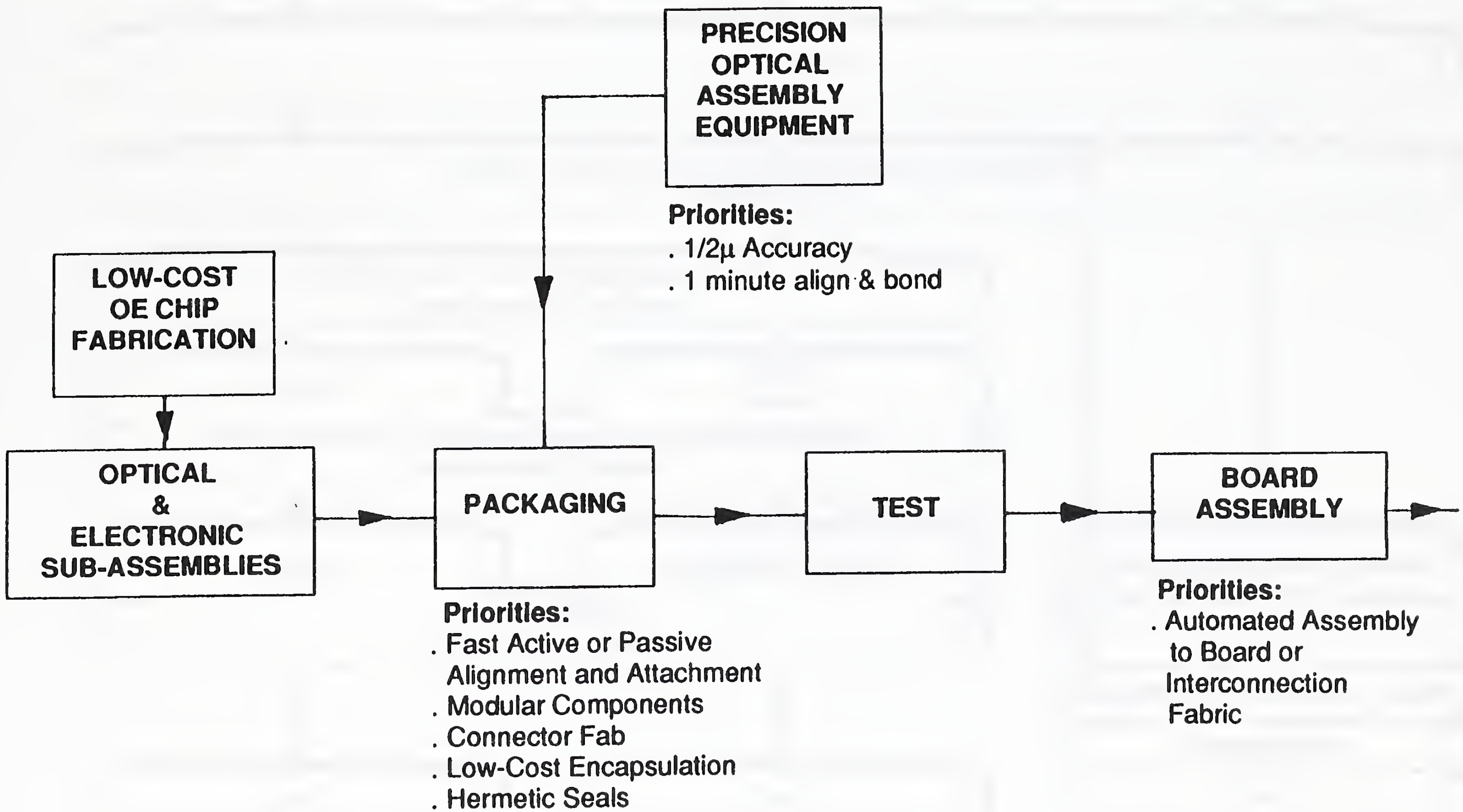
Flip-Chip Assembly

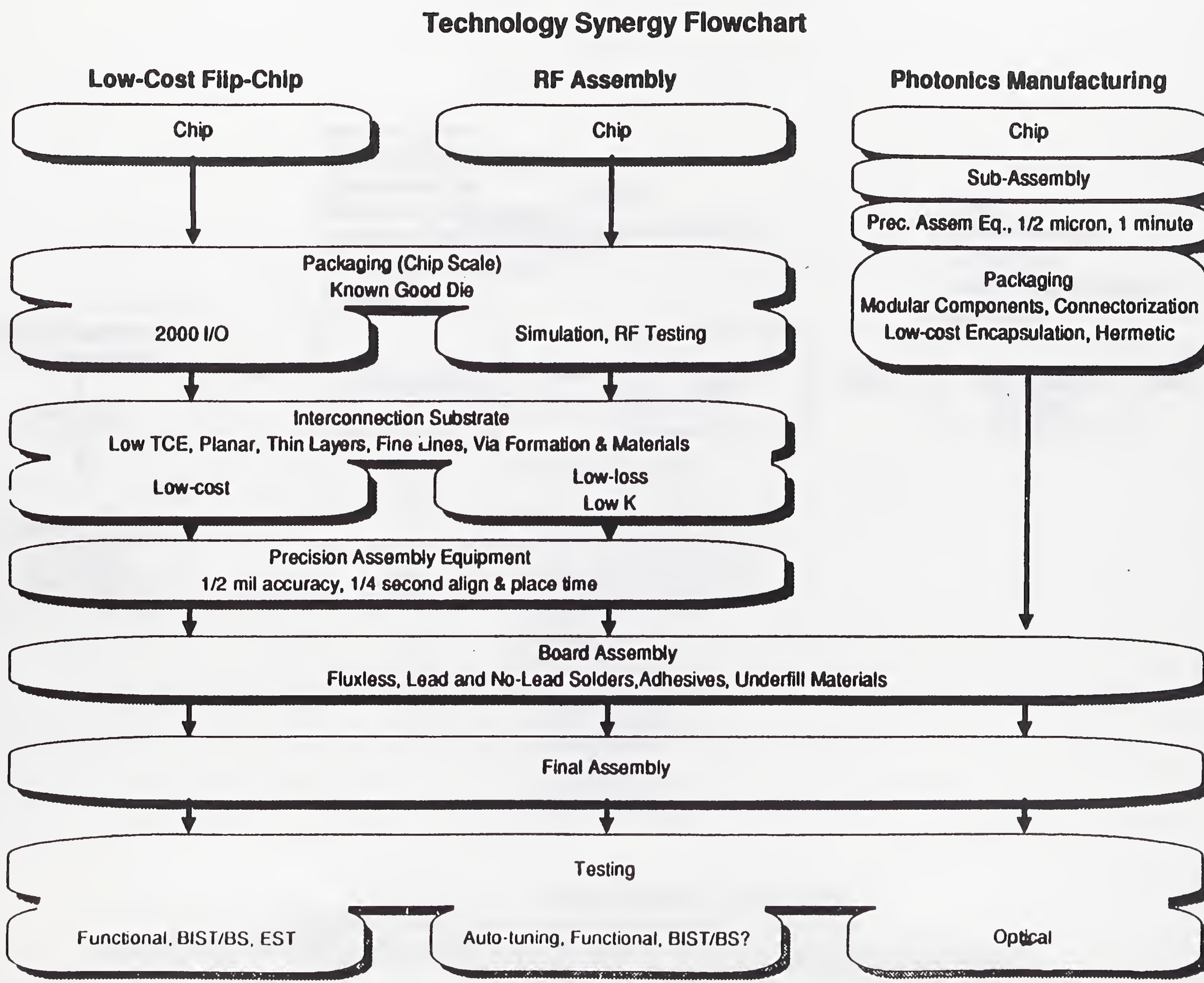
RF Assembly

Photonics Manufacturing

PHOTONICS MANUFACTURING FOR FIBER-TO-THE-HOME (YEAR-2000)

PRODUCT VEHICLES: Low-Cost Photonic Transceiver
Parallel Optical Interconnection





Technology Synergy Flowchart
Low-Cost Flip-Chip
RF Assembly
Photonics Manufacturing
Chip
Chip
Chip
Sub-Assembly
Prec. Assem Eq., 1/2 micron, 1 minute
Packaging (Chip Scale)
Known Good Die
2000 I/O
Simulation, RF Testing
Packaging
Modular Components, Connectorization
Low-cost Encapsulation, Hermetic
Interconnection Substrate
Low TCE, Planar, Thin Layers, Fine Lines, Via Formation & Materials
Low-cost
Low-loss
Low K
Precision Assembly Equipment
1/2 mil accuracy, 1/4 second align & place time
Board Assembly
Fluxless, Lead and No-Lead Solders,Adhesives, Underfill Materials
Final Assembly
Testing
Functional, BIST/BS, EST
Auto-tuning, Functional, BIST/BS?
Optical

IV. Contributed White Papers

Computer Aided Design of Optoelectronic Integrated Circuits

Dietrich Meyerhofer
David Sarnoff Research Center
Princeton, NJ 08543

Optoelectronic CAD

- Sophisticated CAD tools were an essential component in the development of IC technology and reducing the cost of design
- Optoelectronic devices and packaging are even more complex. Their operation depends on the interrelation of many phenomena. Design and evaluation of devices and circuits is a complex process that requires high precision.
- Sophisticated CAD tools are not currently available.
- Sarnoff has developed a CAD architecture that can serve as a basis for a practical sophisticated system. It uses an open architecture and allows the incorporation of individual design tools, developed by different groups on different platforms, into an integrated system.
- Fully developing such a system with broad support by the industry would lead to the development of better and cheaper optoelectronic devices.

Optoelectronic CAD

An optoelectronic CAD system is a key requirement for achieving the development of low-cost optoelectronic modules.

Optoelectronic devices and packaging are very complex. Their operation depends on the interrelation of many different phenomena. This requires very high precision in the design of such devices.

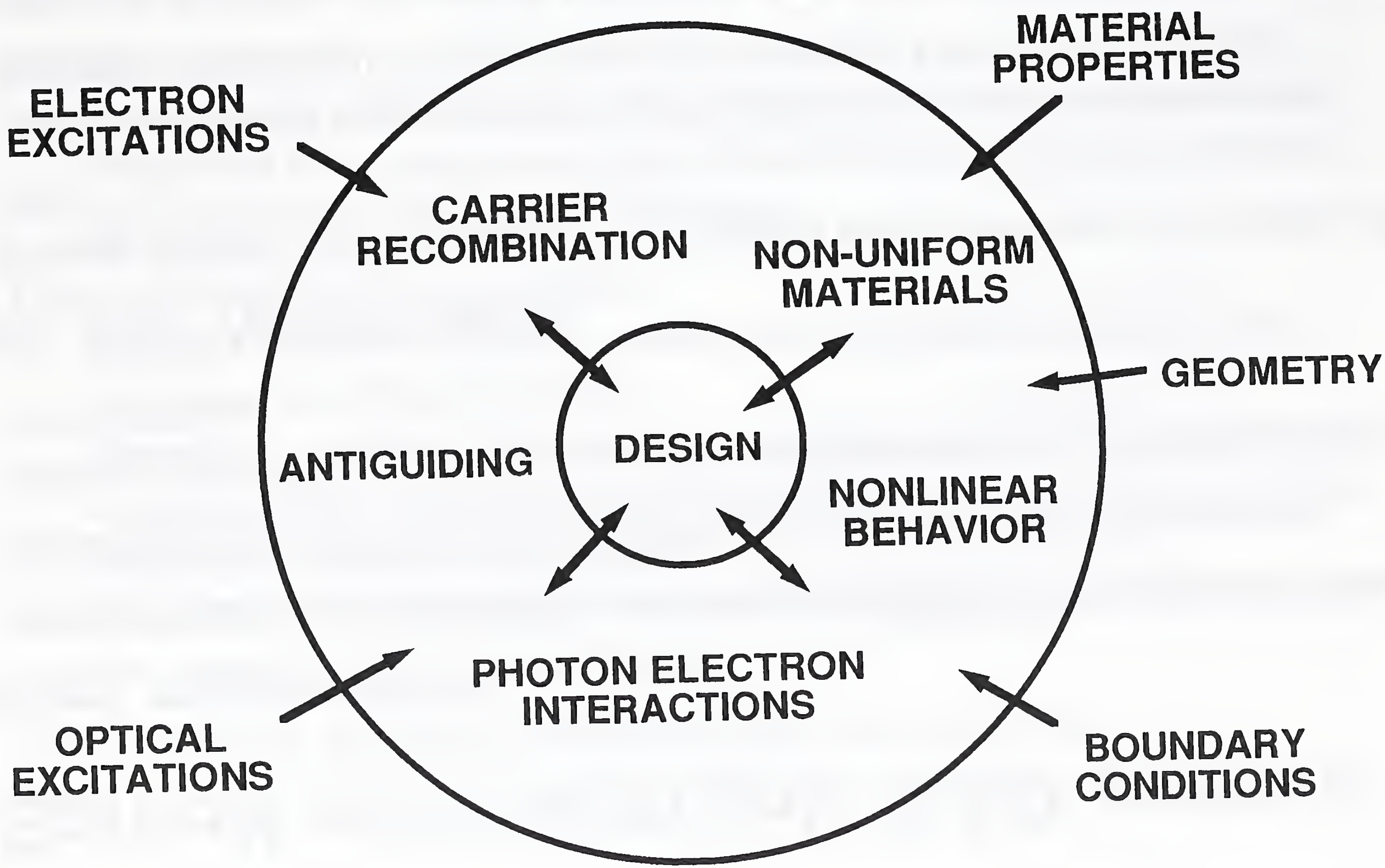
Large reductions in cost of optoelectronic devices are only possible with significant improvement in the design process.

The Sarnoff CAD system provides an answer. It is based on an open architecture. It allows the incorporation of individual design tools, developed by different groups on different platforms, into an integrated system. Thus, it is particularly suited to support the diverse and fragmented optoelectronic industry.

Optoelectronic design consideration

- Many parameters and interactions
- Many different kinds of elements
  - Light sources
  - Waveguides, fibers
  - Refractive, holographic, binary optical elements
- All elements require complex models and many input parameters
  - Three-dimensional variation of properties
- Interactions in one element
  - Charge - optical absorption - optical gain
- Interaction of different elements
  - Feed back

OPTOELECTRONIC DESIGN



Sarnoff

Sarnoff optoelectronic CAD system

Design requirements

- Define material and structural elements of complex devices and circuits
- Model optical sources and nonlinear and electro-optic interactions
- Analyze the optical and electro-optic performance for interaction and optimization

User CAD requirements

- Simple graphic user interface for dynamic programming and transfer of files
- Ability to extend system capability by incorporating new design and analysis modules including routines developed for other systems
- Network multiple computing platforms and other applications to provide computer integrated manufacturing capability

Sarnoff optoelectronic CAD system (continued)

Implementation

- Modular approach

  The system is divided into its components. Each component is described by a macro-module, consisting of individual modules interconnected with data flow wires.

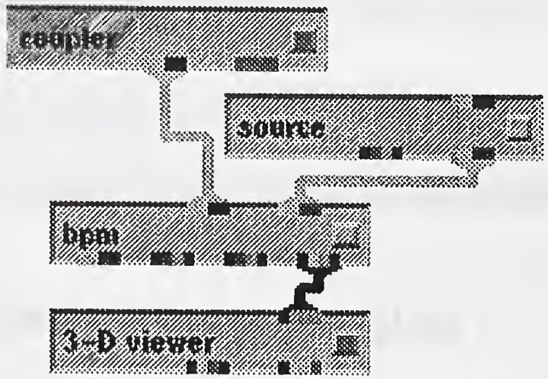
- There are four kinds of modules:
  - Material modules, such as substrate modules or modules that calculate an effective index.
  - Geometry modules deal with boundaries, waveguides and devices
  - Computational modules which calculate the propagation of light within the devices and circuits
  - Visualization modules provide graphic display of the circuits and the results of the computations

- Extendibility to different simulation tools and platforms

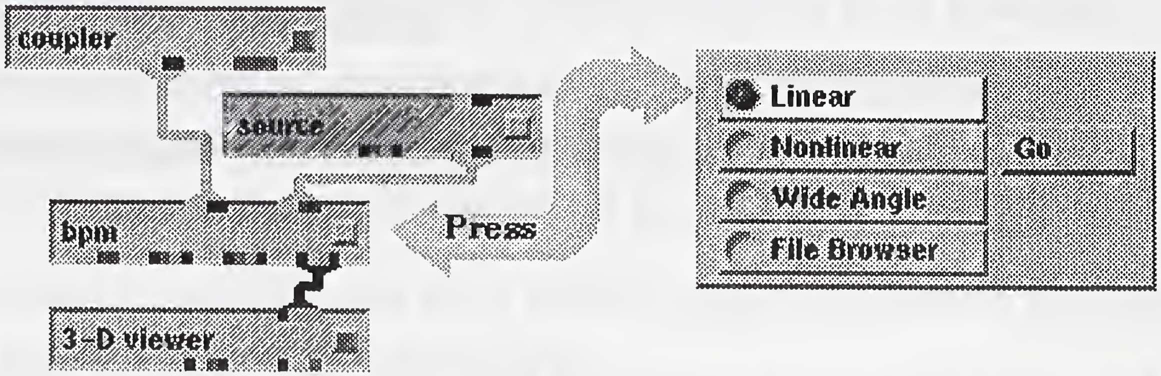
Example: Optical directional coupler

System

The system is broken into macro-modules which are interconnected by wires of different types

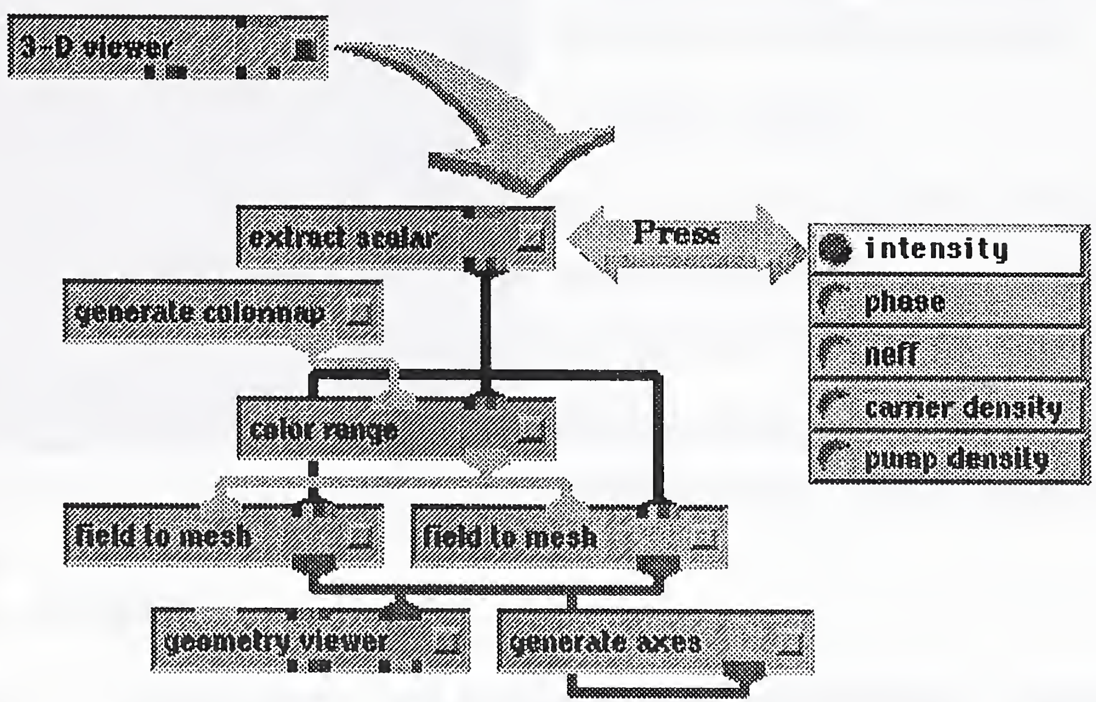


Computation is performed by the BPM module, which can be set to one of a number of different algorithms or to a previously saved simulation



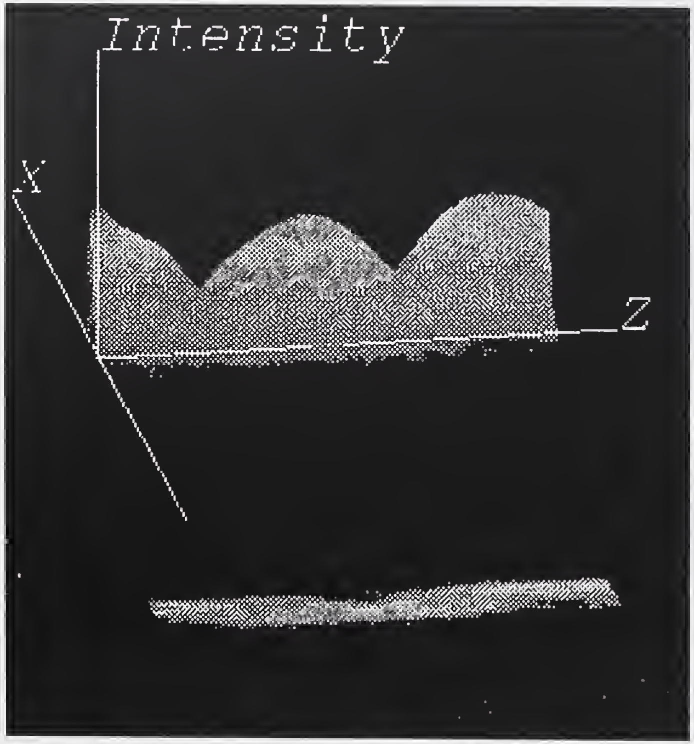
Example: Optical directional coupler (cont)

Macro-modules are made up of interconnected modules each with a panel of specifications



Example: Optical directional coupler (cont)

Graphic output



Graphic output of data graphs or 3-D models are obtained by easy selection

Conclusions

- The design of large and complex optoelectronic circuits requires sophisticated design tools that can model all the components and their interrelationships.
- Such a design tool does not currently exist.
- The Sarnoff CAD system provides a basis for developing an integrated design tool. It is based on an open architecture which can incorporate individually developed modules into an integrated system.
- Use of such a system by the optoelectronic industry would allow the development of innovative, sophisticated, cost-effective devices and circuits.

Development of the GaInN Material System for LEDs and Lasers

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Summary

During the next 10 years, light emitting diodes (LEDs) will experience a paradigm shift in performance and new applications. New markets in power signaling (automobile tail lights, traffic lights, outdoor video displays) and illumination (display back-lights, replacement for incandescent lamps, etc.) will completely dwarf the traditional LED markets, such as indicator lamps and displays. A new material system, GaInN will enable short wavelength green and blue LEDs with an efficiency comparable to red and yellow LEDs, and superior to incandescent lamps. The recent breakthrough by a Japanese company, Nichia, forces the US industry into an accelerated development program at a time when the investment rate in the previous material system (GaAlInP for red and yellow) has not yet peaked. These overlapping development cycles are limiting the industry's rate of investment in the GaInN material system for green and blue LEDs and blue lasers and jeopardizing the US industry's chances to close the gap with Japan.

Evolution of LED Performance

When light emitting diodes, pioneered by Monsanto and Hewlett-Packard, emerged in 1968 their performance was quite limited: The color range of GaAsP/GaAs was limited to the long wavelength spectrum of red around 655 nm and the luminous efficiency was approaching 0.1 lm/W. Even with this marginal performance, LED's rapidly replaced Nixie tubes and started to penetrate indicator lamp applications because of their superior reliability and ruggedness.

By 1973 the first of several generations of improvements in LED material systems occurred. By replacing the opaque GaAs substrate with the transparent GaP the extraction efficiency was substantially improved. Simultaneously, the introduction of a new exciton recombination process expanded the color range from red to yellow-green. This GaAsP:N/GaP material system achieved a 10x improvement in efficiency to 1.0 lm/W. An LPE version of this material system, GaP:N/GaP became the performance leader in the late '70s with approximately 4.0 lm/W at 572 nm and 0.5 lm/W at 565 nm.

In the early '80s Stanley in Japan introduced a new material system, single hetero-junction GaAlAs/GaAs. It was limited to the long wavelength region of red around 650 nm. Its performance was comparable to GaAsP:N/GaP on average, but its best chips were in the range of 2.0 lm/W. By the late '80s both Stanley and Hewlett-Packard were producing a double hetero-structure design on a transparent substrate, GaAlAs/GaAlAs with an efficiency of approximately 10 lm/W at 650 nm.

Progress in organo-metallic VPE growth in the mid '80s resulted in a fourth generation LED material system: GaAlInP/GaAs. A transparent substrate variation of this material system, GaAlInP/GaP pioneered by Hewlett-Packard and introduced in 1994, quickly became the performance leader at any color from red to yellow-green. This system peaked at 20-25 lm/W from 590-620 nm and achieved 7 and 3 lm/W at 567 and 563 nm, respectively.

Evolution of LED Markets

The first generation GaAsP/GaP led to the first solid-state numeric and alphanumeric displays and indicators. For several years in the early to late '70s this material was the technology of choice for hand-held calculators. With the emergence of GaAsP:N/GaP the color range expanded and efficiency improved by 10x. Now LEDs became pervasive as indicator lights and as large numeric displays with digit sizes from 7-25 mm. By 1980 the world's production of LED chips approached one billion chips per month.

Until the mid '80s, the limited efficiency of LEDs restricted their application to environments with benign illumination levels, i.e. in-doors. With efficiency improvements in GaP:N/GaP LPE materials and, especially in GaAlAs/GaAlAs, out-door applications emerged. Most of the earlier out-door applications were still based on using one LED element per indicator function.

At Hewlett-Packard we classify all applications that use one LED element per indicator function as "Small Signaling" applications. The flux requirements per indicator function or pixel is in the range of a few milli-lumen for in-door environments to the range of one lumen for out-doors.

In the late '80s the legislation for a center-high-mount-stop-light (CHMSL) for cars sold in the USA opened another class of applications: "Power Signaling". In this new class of applications the flux requirements exceed the flux that can be generated by a single LED. Power Signaling applications range from a few lumen for a CHMSL to several hundred lumen for a traffic light. The early LED based CHMSLs used 50-100 conventional 5mm lamps to accomplish this function. Recent designs achieve the same function with 10-20 custom designed lamps.

CHMSL designs bring up an important difference between Small Signaling and Power Signaling applications. In a Small Signaling application one needs one lamp per function or pixel. A 2x improvement in efficiency does not translate into half a lamp per pixel. In other words, the market will not reward a substantial improvement in performance with a correspondingly higher price. In our experience, a 2x improvement in efficiency will, at best, result in a 10% price premium in the market. In the Power Signaling market the situation is quite different. A 2x improvement in efficiency will translate into a 2x reduction in the number of elements that are needed to generate the specified flux. Since the LED chip represents only 10-20% of the cost of a lamp, it is advantageous to go for a 2x performance improvement even by doubling the chip cost. In other words, the Power Signaling market requires investments in performance improvement that the Small Signaling market would not pay for. This paradigm shift leads to the conclusion that LED material systems for Power Signaling applications must be developed to a much higher level of performance than the earlier material systems which were only serving the Small Signaling market.

There is another important issue that emerged with the Power Signaling applications: the life-time cost of power consumption. An LED based CHMSL or stop light and turn indicator may not have much impact on the gasoline consumption over the life of a car - it certainly will not influence the buying decision - but the power consumption of a red traffic light will significantly influence the lifetime cost. At 20 lm/W red LEDs are at least 4x more efficient than filtered incandescent lamps. Converting the red lamps in traffic signals to LEDs results in a power cost saving of $500-$1000 per year per intersection. Here in California the city of Fresno has converted all red traffic lights to LEDs and the power company, PG&E, provides an incentive to municipalities to convert traffic lights.

Before describing the next evolution in the LED market, it is necessary to understand the performance limitations of LEDs in the short wavelength green and blue range of the spectrum.

Blue/Green Hole and Nichia Breakthrough

The present range of LED material systems is limited to the color range from red to yellow-green (670-563 nm). Short wavelength green and blue require material systems with a much wider energy bandgap than the 2.3 eV of GaP. Candidates are SiC, ZnSe and GaN.

The oldest system, SiC has been in the market for the last 20 years, but hardly made it beyond the curiosity level. The indirect band gap has limited it to the range of <0.1 lm/W. The products were used as color standards. Moderate volume applications such as high beam indicators in cars are emerging now.

Recent progress in ZnSe has led to excellent levels of efficiency in both LED and laser structures. But the inherent instability of this II-VI material system has resulted in unacceptably short operating life, hours instead of years.

The third candidate, GaInN has also had its share of frustrations. It has been difficult to dope this wide band gap material to form pn junctions, a requisite for LED operation. While recent progress in this system was quite encouraging, everyone was caught by surprise when a small Japanese chemical company, Nichia, introduced blue and green LEDs in 1993-94 with efficiencies of 2.5 lm/W at 440 nm and 8 lm/W at 510 nm. The Nichia LEDs were grown on an insulating and transparent substrate, sapphire. In spite of the unprecedented dislocation density of 10exp11/cm2 these diodes achieved quantum efficiencies of 3%. Suddenly, "out of the blue" came a new material system that had comparable performance and reliability to the red/yellow/yellow-green systems developed over the last 30 years.

The present performance of the most relevant material systems is illustrated in Fig. 1. The unit of efficiency is lumen/ampere. This unit is most meaningful in the Small Signal market. In the Power Signaling market the preferred unit is lumen/watt. To convert lm/A into lm/W the units of Fig. 1 should be divided by the voltage applied across the LEDs, i.e. divide by 3.5V for GaInN and SiC and by 2V for all the other material systems.

Significant New LED Applications

With the emergence of blue/green GaN LEDs, the quest for a "complete" LED system capable of generating white light with a broad color gamut seems to come to an end. With a potential RGB performance of 20/30/10 lm/W in the three primary colors, LED based products will be able to attack a subsegment of the incandescent lamp market, even if these lamps are used for "Illumination" purposes. Battery operated portable devices will benefit from the LED's higher efficiency, practically unlimited operating life and superior vibration and shock tolerance. Back-up lights in automobiles will have the same thickness as LED based tail/brake lights and turn indicators, thus eliminating the need to punch large holes into the sheet metal forming the tail end of a car. Since the Illumination market is one to two orders of magnitude larger than the LED indicator and display market, a small penetration of cost insensitive niches will substantially increase the LED market. Today's production of 3-4 billion chips per month could grow tenfold over the next 15-20 years. Then the GaN material system could emerge as the most important LED system. For the generation of white light two out of every three chips will be GaN based: short wavelength green and blue. By the year 2010 GaN LED chips could outnumber all other LED chips.

Need for a Catch-up Program

Nichia has put the GaN system on the LED map as a viable and, possibly as a dominating contender. Hewlett-Packard is today's leading LED supplier on a global scale measured both in LED performance and in LED based product sales. Nichia's breakthrough is a threat to HP's position. But it can be met with a timely and aggressive response.

The successful development of a new LED material system is quite expensive. As a reference, the development of the GaAlInP system on both absorbing and transparent substrates has cost HP well over ten million dollars to date and the investment will more than double by the time of its completion around the year 2000. This cost includes only the engineering cost to develop epi growth, wafer processing and proof of acceptable chip reliability. It does not include the cost of developing products that use these chips nor does it include the cost of capital equipment to develop or manufacture GaInN chips.

The cost of developing the GaN system will be comparable to the cost of the GaAlInP system or higher. The GaN system will benefit from the OMVPE experience of the GaAlInP system. But it faces a substantially more complex substrate problem. While sapphire has proven its feasibility for reasonably performing LEDs, it may be unsuitable for lasers and might not be the choice for high performance LEDs. Better lattice-matched substrates such as SiC and even bulk GaN have to be explored.

Impact on Blue Lasers

The need for blue lasers is driven by optical storage. Two kinds of blue lasers will be needed: (1) a 10 mW power laser for the read/write/erase function in magneto-optic storage systems and (2) a lower power laser for the read function in CD-like read only memories. The use of these storage systems in consumer electronics applications will force the low power laser to a market price of $2.00 to $3.00 similar to today's 780 nm CD lasers. The power laser will be more expensive and $10.00 seems to be a reasonable target.

Market prices will be set by the lowest cost producers. It is expected that the Japanese competitors will produce blue lasers incrementally on high volume GaN LED production lines. For instance, a producer with a 20% market share may manufacture 1M blue lasers per month in addition to 100-200M LED chips. It is quite obvious that such an integrated producer will have a lower cost structure than a stand alone facility that cannot spread its overhead. Only a country with a substantial LED based infrastructure will be able to successfully compete against Japanese suppliers.

Impact on Defense Technology

A major LED based GaN development program will create the technology base and infrastructure to effectively produce GaN based products from LEDs to lasers. The following three areas are of particular importance:

- Substrates: Sapphire substrates present a very poor lattice match to the growth of GaInN epitaxial layers. A base to supply high quality SiC substrates must be created since sapphire is most likely unsuitable for laser and high performance LED production.

- Epi Reactors: The present generation of epi reactors is inadequate for multi-wafer production use. Cooperation with at least one epi reactor manufacturer will assure a US position on this crucial technology.

- Source Material: High quality gases are needed to grow state-of-the-art epitaxial layers, the most crucial step in any LED or laser production process. Working with gas suppliers will advance the quality and capability of US based suppliers for GaN materials as well as other compound semiconductors.

At the product level, blue lasers for high density storage are of greatest interest to the defense industry. But, there are a range of other products and applications that are worth mentioning:

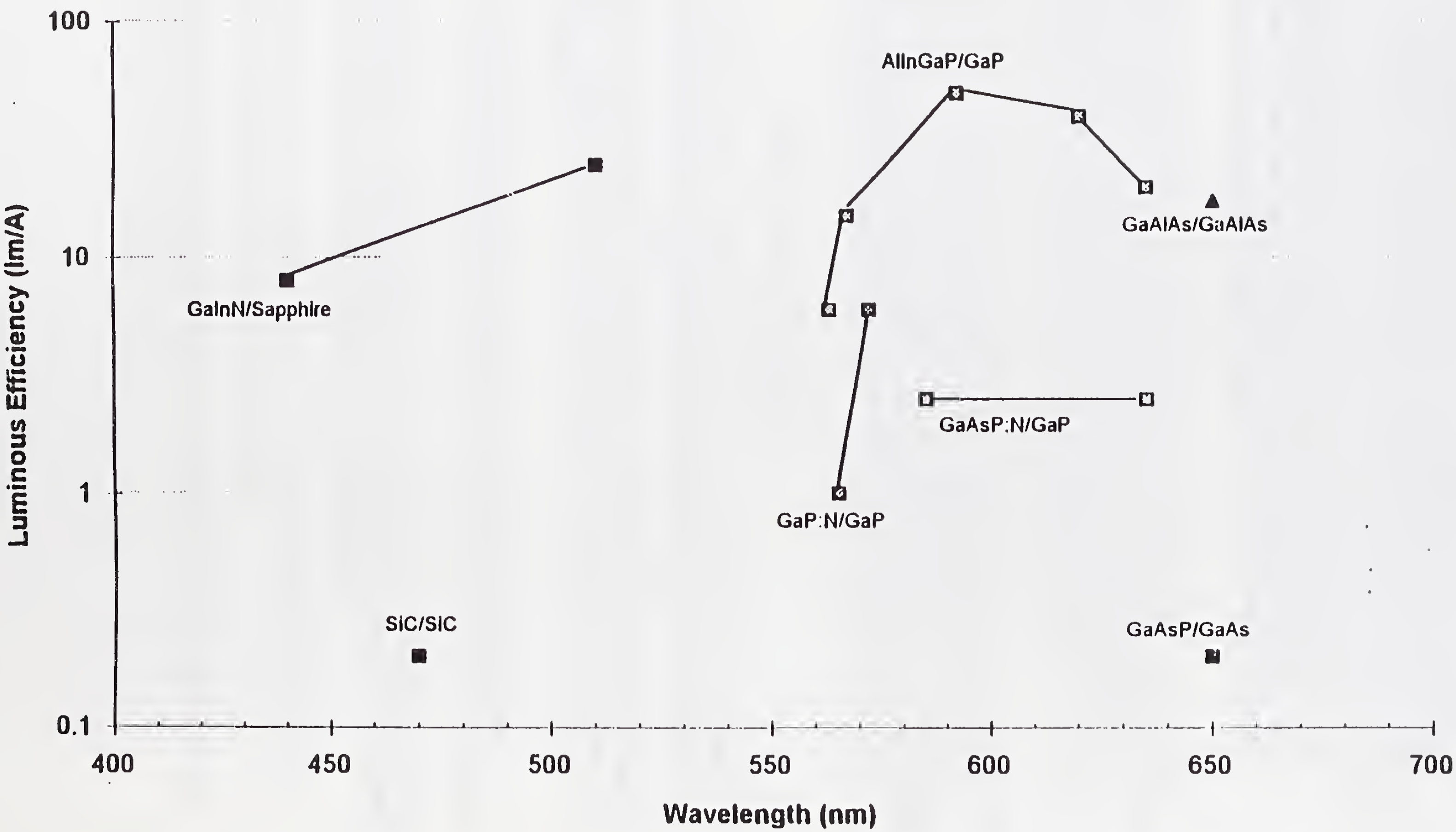
- Green Lasers: The GaInN material system has a direct bandgap extending well into the green spectrum. Green lasers for submarine communication should be feasible.

- AMLCD Backlight: With efficient green and blue LEDs, one should be able to design efficient back-light systems for active matrix LCD displays. These back-light systems reduce the complexity of the active matrix display by a factor of 3x and eliminate the costly color filter. The impact on cost reduced active matrix LCD could be substantial.

- Battery Operated Light Sources: Since LEDs can match or exceed the efficiency of halogen lamps today, and probably exceed their efficiency by 2-3x in the near future, we expect a major impact on battery operated light sources. Superior shock and vibration performance will add significant value.

- Fiber Optics Using Plastic Fiber: Plastic fiber has a narrow transmission window in the red region at 650 nm. Two adjacent C-H resonances limit the attenuation floor to approximately 0.15 db/m. There is a much wider attenuation window in the green range of the spectrum, but the available sources are too slow. GaN based sources with a direct bandgap should enable fiber optic communication in this green window.

Spectral LED Performance



PROGRAM IDEA

NON-PROPRIETARY

ALPHA-NUMERIC AND FLAT-PANEL DISPLAYS BASED ON SEMICONDUCTING POLYMER-LIGHT-EMITTING DIODES

A White Paper submitted to

Program Ideas
Advanced Technology Program
National Institute of Standards and Technology
A430 Admin. Bldg.
Gaithersburg, MD 20899-0001

submitted by: Los Alamos National Laboratory

Project Manager: Dr. David E. Watkins
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Display technologies have come to dominate our interaction with the technological world, in the form of simple indicators, alphanumeric displays, displays controlling appliances, televisions, and computer CRTs (cathode ray tubes). As the world continues to push for increased automation and "smarter" appliances, the need for more sophisticated displays also grows. This trend has accelerated as the microprocessors at the heart of many of these applications have receded into the background, hidden behind increasingly "user friendly" interfaces. As a result, demand from users for easy to understand custom visual information displays continues to grow. At the same time, demand for lower cost displays has also increased. All current display technologies, (including light emitting diodes, liquid crystal displays, electroluminescent displays, plasma discharge displays, and vacuum fluorescent displays), are under pressure for increased performance and size at reduced cost. Although each of these technologies occupies an important niche while continuing to incrementally improve its capabilities, this progress is slow. The recent development of LEDs based on semiconducting polymers (PLEDs) presents a fresh approach to many of the existing problems. It could, therefore have a significant impact on the continuing evolution of the display industry.

Today, Japan dominates the global display market. One estimate by the Department of Energy puts the Japanese share at 98% and the US share at less than 2%. A major change in this unfavorable position is certainly needed if the U.S. is to gain control of the production of displays for computers, as well as other sophisticated high-information content displays. It is not clear, however, whether this change can best be achieved through incremental improvement of technologies in which Japan has an entrenched position (due to its extensive capital investment and commitment of research manpower), or through US development of an alternative technology. The government is already supporting several display initiatives that compete head-on with Japanese technologies. By providing an alternative approach, the opportunity presented by polymer light-emitting diodes fits very nicely into a multi-component strategy to bolster overall US display manufacturing capability.

Six years ago scientists at the Cavendish Laboratory in Cambridge, England demonstrated that light emission from the polymer poly(*p*-phenylene vinylene) can be stimulated by sandwiching it between a pair of appropriately chosen metal electrodes and applying a bias voltage. Since this seminal work, electroluminescence from a number of different semiconducting polymers has been reported. Notable improvements in efficiency and operating voltage

have been achieved in Professor Heeger's laboratories at the University of California in Santa Barbara. Light output efficiency was increased by an order of magnitude, resulting in PLEDs comparable in brightness to conventional red LEDs. The color of the emitted light depends on the polymer chosen, and colors from blue to red are possible.

Research on polymer light-emitting diodes demonstrated a number of attractive characteristics (and indicated many of the important issues requiring further investigation) of these devices. The principal problem preventing this technology from immediate commercialization is the lifetime of the PLED devices; currently, operating lifetimes range from a few hours to a few hundred hours.

The important device features are the following:

- Colors throughout visible spectrum;
- External efficiencies of approximately 3 lumens/W;
- Operating voltages of order 5 V;
- Simple methods of device fabrication (processing the luminescent materials from solution);
- Novel shapes and robust mechanical properties (flexible, curved surfaces, *etc.*).

Improving US Technological Position

The trends in the information display markets are toward higher information density, lower power consumption, and lower cost. All existing display technologies have difficulty meeting one or more of these goals. Although considerable progress is being made, the opportunity for a new, lower cost technology to have a significant impact certainly exists. Polymer LEDs (PLEDs) represent a new technology that has the ability to challenge some of the existing approaches for display and lead to the development of new areas of application outside the display arena.

Today, Japan dominates the global display market. One estimate by the Department of Energy puts the Japanese share at 98% and the US share at < 2%. A major change in this unfavorable position is certainly needed. It is not clear, however, whether this change can best be achieved through incremental improvement of technologies in which Japan has an entrenched position (through their extensive capital investment and commitment of research manpower) or through US development of an alternative technology. Clearly, the latter approach is preferable, but the risks inherent in any

unproven technology indicate that both approaches should be pursued. The government is already supporting several display initiatives through the DOE Microelectronics and Computer Consortium "Fast Start" study, DARPA's display consortium, and NIST's American Display consortium. The opportunity presented by PLEDs provides an alternative approach and fits very nicely into a multi-component strategy to bolster overall US display manufacturing capability. PLEDs build upon our strengths and attack some of the technological weaknesses faced by existing technologies. A list of the relevant technologies and their strengths was recently compiled by the Council on Competitiveness in a document entitled *Gaining New Ground* :

COMPETITIVE POSITION OF SELECTED US TECHNOLOGIES		
US COMPETITIVE	US WEAK	US LOSING or HAS LOST
Materials & Processing *Chemical Synthesis* *Photoresists* *Polymers* *Polymer Matrix Composites*	Electronic Components *Photonics*	Materials & Processing *Display Materials* Electronic Components *Electroluminescent Displays* *Liquid Crystal Displays* *Plasma & Vacuum Fluor - escent Displays*

The US has established strengths in polymer processing and materials science as well as a great deal of experience in novel chemical synthesis. The infrastructure supporting these technologies are a potential source of advantage in the development PLED alphanumeric and more advanced displays. It contributes the ability to purchase (or contract the synthesis of) a wide variety of specialized organic chemical reagents for the development of new polymers, the manufacturing know-how to develop techniques for coating large areas of substrate with a well controlled thickness of polymer, and to fabricate multi-segment devices and interface them with appropriate drive electronics. Further development of these PLED support technologies will also benefit the field of Photonics. A partial list of specific areas where such scientific knowledge and technology gains may be made are summarized in the following table:

POTENTIAL SCIENTIFIC and TECHNOLOGICAL BENEFITS from a POLYMER LED PROGRAM	
SCIENTIFIC KNOWLEDGE	TECHNOLOGY
Synthesis of new compounds	Degradation of EL polymers
Physics & chemistry of polymer / metal interfaces	Deposition methods for EL polymers
Rheology of thin polymeric films	Encapsulation of electrically active polymers
Molecular modeling	Understanding polymer heterostructures through use of transport layers in PLEDs
Greater understanding of polymer EL	Fabrication of multi-character PLEDs
	Study of cost issues associated with EL polymers
	fabrication of Light Panels

Estimate of PLED Market Potential

Some idea of the magnitude of the display market is available from several sources. The survey chosen for this analysis is from Stanford Resources Inc., quoted by E. Schlam at the *Society for Information Display* Conference held in 1991. Data from the many market surveys examined, although all dependent on subjective factors impossible to eliminate, did show a broad consensus with the trends discussed in detail here. Market dollar value and number of units for the years 1992 and 1997 are presented for those display technologies with which PLEDs can be expected to compete, *i.e.* for all display types with the exception of CRTs. Total market size for LED (light emitting diodes), VF (vacuum fluorescence), LCD (liquid crystal displays), Plasma, and EL (Electroluminescent) displays in aggregate was estimated at about $4.5 bn in 1992, and is expected to rise to $10.1 bn in 1997. The CARG (cumulative average annual rate of growth) over this period would be 18%. Even without LCDs, the display market will rise from about $1.6 bn in 1992 to $3.0 bn in 1997.

By 2002, assuming a modest percentage of the total display market is captured, the PLED market will approach $3 Billion. This ignores the contribution of any of the new non-display applications which might add as much as $ 1 bn. Not only would this contribute directly to US Gross Domestic Product, it would also reduce the balance of payments by taking market share from competing technologies manufactured in the countries of the Pacific Rim.

Benefits of an R&D program

Polymer LEDs are at a stage of development analogous to that of inorganic compound semiconductor LEDs in the early 1960s. Early work by Holonyak in 1962 showed that light emission from $GaAs_{1-x}P_x$ could reach values of approximately 0.1 lm/Watt. Today's commercial red LED of $GaAs_{1-x}P_x$ doped with nitrogen now have efficiencies near 1 lm/Watt and have been used extensively for the last two decades. PLED efficiencies are presently of order 1-3 lm/Watt, a remarkable achievement considering it is less than six years since the first announcement. The technology is in its infancy and needs to be developed.

Successful completion of such an ambitious R&D program will have an important impact on the U.S. economy. A conservative estimate suggests a $3 Billion market will result through the displacement of existing display technologies produced by Pacific Rim countries. Success will, therefore , not only directly enhance the US Gross Domestic Product, but will decrease the balance of payments deficit by reducing imports.

"Cost Effective Manufacturing Technology for Vertical Cavity Surface Emitting Lasers"

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COST EFFECTIVE MANUFACTURING TECHNOLOGY FOR VERTICAL CAVITY SURFACE EMITTING LASERS

ABSTRACT:
In recent years, there have been many advances in the performance of Vértical Cavity Surface Emitting Lasers (VCSELs). The performance of these devices promises to open new markets in optoelectronics. The key new products are centered around an established capability in a new type of semiconductor lasers known as Vertical Cavity Surface Emitting Lasers (VCSELs). A microphotograph of a VCSEL is shown in Figure 1.1. These lasers can be manufactured and tested in monolithic form, and do not require cleaving as do conventional edge emitting semiconductor lasers. Arrays of these lasers which occur almost naturally in monolithic formats, can be used for parallel data communication links in which byte wide data is transmitted in parallel, to achieve greater than an order of magnitude increase in transmission bandwidth over conventional time division multiplexed single channel systems. We are presently developing lasers for short haul applications at 980 nm and long haul lasers operating at 1310 and 1550 nm. These long haul applications include fiber to the home(FTTH), fiber to the curb,(FTTC), cable television signal distribution, intra continental distributed computing and replacement of the more expensive edge-emitting DFB lasers now in use in telecommunications. Research in red, green, blue and UV VCSELs is also under way. These shorter wavelength VCSELs have many new applications including laser printing, high density storage, high definition displays and medical applications. For these products to be successful, *low cost, high reliability* manufacturing technology is needed.

This white paper proposes an approach to low cost manufacturing technology, using innovative process technology coupled with in-situ monitoring with iterative feedback control of critical material growth and wafer fusion wafer device processes which can be directly result in greatly improved yields and lower device manufacturing costs

TECHNICAL APPROACH:

The VCSEL manufacturing process can be divided in to 5 main areas prior to approval for manufacturing:

1. Epitaxial Material Growth

2 Wafer Level Processing and Fusion

3 Wafer Level Device Processing and Testing

4 Wafer Sawing, Device Packaging and Reliability testing

5 Environmental Qualification and Reliability Testing

1. Epitaxial Material Growth

The method for manufacturing epitaxial materials is many times a result of type of materials needed for the specific device performance requirements. GaAs based VCSELs typically have used Molecular Beam Epitaxy (MBE), which has a typical growth uniformity of 2 to 5% across a 2 to 3 inch wafer. InP based devices for longer and shorter wavelengths typically have used Metal Organic Vapor Phase Epitaxy (MOVPE). Until recently, many researchers have insisted that MBE has more accurate control of deposition parameters, even though growth rates are slower and equipment costs higher.

However it has recently been shown that the highest performance VCSELs even in the GaAs/InGaAs device family (780 - 980 nm) have been achieved with MOVPE epitaxial material as shown in Figure 1. These devices are compared with typical MBE grown devices as shown in the figure.

In addition, new MOVPE reactor designs have resulted in wafer growth uniformities of better than 0.2 % in two inch wafers, a control which can be extended to larger 3 and 4 inch wafers. This remarkable uniformity is achieved through innovative reactor design, real time in-situ monitoring and growth rate and thickness monitoring, together with real time analysis and feedback control of environmental and growth parameters so as to automate the growth process. See Figure 2. This is the level of uniformity and control needed for high manufacturing yields necessary for high performance, high reliability low cost manufacturing.

2. Advances in VCSEL Device Processing

Device level processing can also be greatly simplified by use of recently developed oxidation processes for improved device performance and yield. Conventional ion implant processes cause internal device damage, thermal lensing and higher current and voltage thresholds in devices. resulting in higher driving powers necessary for equivalent device performance. This higher power requirement naturally leads to poorer reliability due to the greater internal heating of devices for an equivalent power output. Figure 3 shows a comparison of the present ion implanted VCSELs and the newer devices using oxide processing, which have the high efficiencies shown previously in Figure 1.

3. Device Packaging ans Reliability Testing

The real key to higher reliability in VCSEL devices lies in the lower voltages and powers that are required by VCSELs to provide a usable optical output, typically from 0.5 to 3 dBM. Furthermore, the short cavity design compared to conventional edge emitting lasers also results in single mode power at much lower input powers. See Figure 4. The ability to perform wafer level testing prior to dicing and without the need for facet cleaving required in edge emitting lasers, not only simplifies manufacturing but also allows more automated packaging. Even monolithically integrated and aligned microlenses can be fabricated directly in the III-V device material, resulting in focussed, aligned laser beams in multiple laser arrays. See Figure 5. In summary, many new processes can be intelligently integrated into a low cost, high reliability manufacturing process, which will result in the cost breakthrough necessary to bring low cost VCSEL arrays into high volume low cost optoelectronic circuit and system applications.

Manufacture of
Very Large Scale Integrated Optics (VLSIO)
with
Three Dimensional Packaging

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ABSTRACT

We have demonstrated the feasibility of manufacturing 100,000 electro-optical components per square centimeter using 0.5 micrometer lithographic resolution, with the most compelling application being that of digital logic. We show that by use of high index ratios between the cladding and guide, Ultra High Confinement (UHC) waveguides can be created, leading to compact devices and sharp bends. Furthermore, with the use of binary diffractive optics, these Very Large Scale Integrated Optical (VLSIO) circuits can be interconnected in three dimensional stacks with high density connectivity. We show how a system with wide alignment tolerances during packaging can be created. We give special attention to a non-uniform grating coupler between a compact waveguide mode and a large Gaussian profile single mode beam. This coupler is a critical component for interconnects, allowing efficient coupling between various beam shapes and compact devices. The size of the integrated optical devices is 10 to 100 times smaller than present waveguide resonators, resulting in much higher speed and lower power. We have analyzed these waveguides and wave-scale passive components using 3D Vector Field Finite Element Methods and microwave scaled experiments.

The most impressive example of manufacturing technology in the information age is that of VLSI electronics. From the view of an individual in use of computing power, it would appear that computers have become two times faster every two years, with over a thousand-fold performance increase during the last 20 years. However, this phenomenon has not been so much a result of advancement in transistors, but rather in the manufacture of systems. Computers have simply become less expensive every year, allowing the customer to purchase more power every year. Individual logic gates upon which the computer systems are based have become faster, but only in proportion to the decreasing lithographic linewidths. This ten fold improvement in electronic logic gate speed over the last 20 years, as a result of manufacturing size improvements, is only a small part of the thousand-fold gains seen by the consumer, which is mostly from greater affordability. This is not just a point of view, but an important statement on the limits of computing advances. For if computers were simply getting faster, equal advances in computing power should occur from personal computers to supercomputers. However, as can be seen from Figure 1, there has been a convergence such that supercomputers, workstations, and high performance personal computers are all now within a factor of five of each other in performance, compared to the 10,000 ratio in performance that existed 20 years ago. Supercomputers have only improved by a small factor, only slightly greater than the improvement in logic gate speed. This convergence in computer performance illustrates that computer power cannot be easily improved, even for great increases in price. Over the last 20 years, most all gains in the computer revolution have been in manufacturing and price.

The resulting expansion of computing has been a great benefit to society, but individual computer technology has not greatly improved.

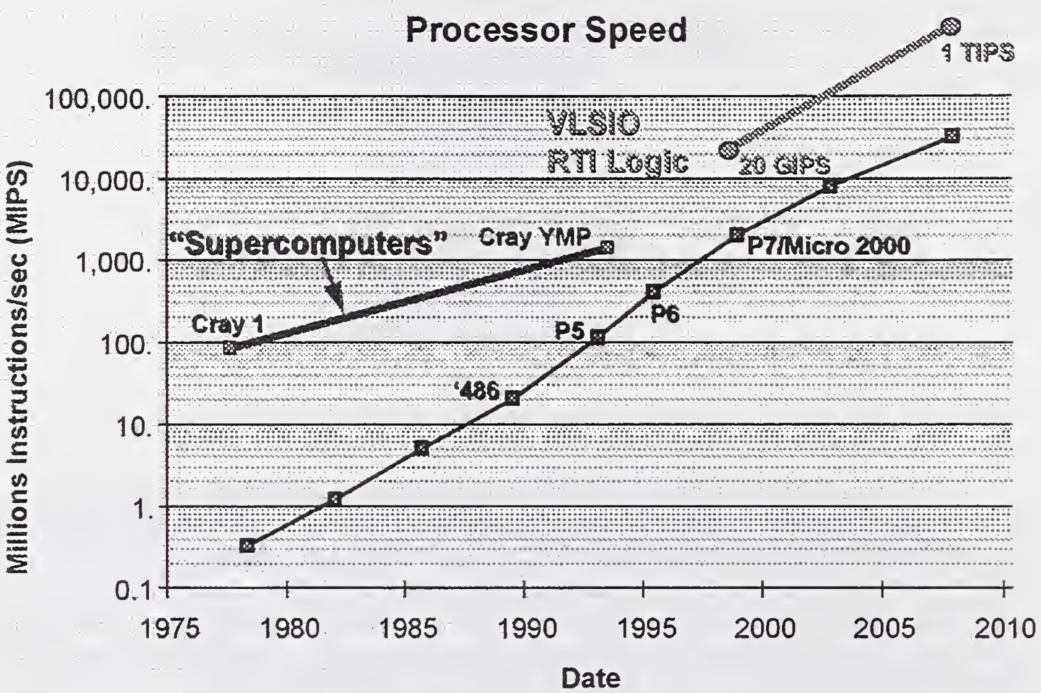

Figure 1. Serial Speed for PCs and Supercomputers with Projections for Very Large Scale Integrated Optical Computers.

Furthermore, up to now, improvements in integration levels that arose from the manufacturing improvements could be used to directly advance the computer power in proportion to the improvements in integration level. The architecture could simply incorporate more concepts already proven in supercomputer technologies. However, serial supercomputers reach a rapidly diminishing return in performance with increasing logic counts beyond about 150,000 logic gates. The Intel Pentium with about 3 million transistors has approximately this number of logic gates, with the majority of transistors used for cache memory. At this level of complexity, one can perform instruction pre-fetch, decode, and execution, pipelined floating point conversions and math, conditional branch prediction, and other proven concepts for performance. With increases in gate count beyond this level, one can use the gates to create multiple piplelines, speculative execution along several branches with the wrong branches discarded, and hardware implementations of important math functions. But the increase in program performance from these extensions no longer improves in proportion to the number of logic gates (Hennessy and Patterson). Similarly, parallel computing concepts also have decreasing efficiencies with increasing integration levels, except for very specialized applications. The recent convergence in serial computer speeds is a result of the rapidly diminishing returns for serial computer architecture performance with increasing logic gates beyond the levels used in VLSI today. The predicted future performance for electronic computers as shown in the Figure 1 is for maximum performance. The general purpose computing performance of these future processors using parallel super-scalar architectures could improve at a much slower rate than the peak speeds as the average performance may no longer track the peak serial speed performance.

Optics has the capability of dramatically improving this fundamental computer performance via the reduction of capacitance and intrinsic high bandwidth communications. Yet optical devices have not replaced silicon VLSI to date. The reason is very simple. The optical devices to date have not had

significantly greater performance with equal computing capability and similarly low manufacturing cost. A large number of papers and books in optical computing (Barrekette, Stroke, Nesteteikhin, and Kock; Gibbs, Mandel, and Smith) document the great efforts spent to obtain higher performance with optics on a particular component of the computer system. In some cases this optical computing effort has been successful, but at an extreme cost penalty for manufacture and laser supply. The approach taken here is to simply use the same manufacturing techniques that have been successful for silicon electronics and apply them to optics (West). The individual digital logic components are improved in speed and power by direct optical connections at the gate level. Electronic logic gates in production today have propagation delays in the low 10's of picoseconds in low fanout ring oscillators. But as fanouts are added and wires become longer, the logic gate delays rapidly rise up into many 100s of picoseconds. This phenomenon has been observed with all electronics technologies from Si BiCMOS to GaAs HEMTs. The reason is straightforward. For example, a wire with an oxide and metal width twice the oxide thickness ($d_2 = w/2$) has a capacitance of 30 fF/mm independent of linewidth (see Fig. 2). In practice, the capacitance is 100s of fF/mm because of the thin oxides desired. Since typical digital circuits work with several volts and sub-milliamp currents, the natural resistances are several thousand ohms. Charging a mm length wire then takes 100s of picoseconds, independent of linewidth. A typical fanout for logic is three, and the size of electronic circuits are now exceeding one centimeter. This places serious restrictions on clock speed for logic with electronic wiring. With removal of the capacitance in the fanout logic gates and wiring by using optics, the fundamental electronic logic can reach its natural speed below 10 psecs. Furthermore, the power dissipation in electronics also arises from the charging of these capacitors and is similarly reduced with the use of optical connections. Very Large Scale Integrated Optics (VLSIO) provides high bandwidth interconnections using optical waveguides as transmission lines directly connected to the logic gates. The manufacture of these components can be done with standard photolithography methods. Many efforts are being made to replace the interface pins used in electronic packaging with optics. It is possible to improve the nanosecond chip connection speed down to the 100s of picosecond on-chip speed. The problem is that silicon is not an optical emitter and only poorly performs other optical functions. So the effort of connecting silicon to optical devices has replaced the effort of connection to an external pin. Which technique is best is very much an engineering function. In contrast, optical connection at the gate level has very fundamental advantages for optics which electronics has difficulty surmounting, practically guaranteeing the migration of computers to optical circuitry at some point in time.

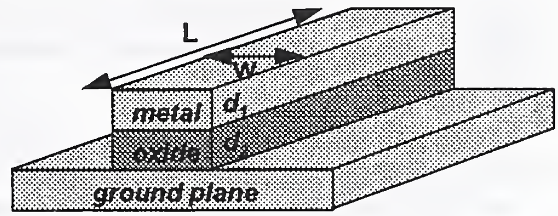

Figure 2. A typical electrical wire with greater than 30 fF/mm capacitance

The VLSIO approach also has additional fundamental advantages in manufacture and packaging over electronics. With optics, the logic circuits can be distributed over a number of lower device density chips, but stacked upon each other and connected by lens arrays (see Fig. 3). Packaging with an array of diffractive lenses is lower cost than wire bonding to pins as the chip packaging is nearly complete upon fabrication. A logic chip simply needs to be stacked on top of another chip to be coupled as illustrated in Figure 3. The surface connector array can yield over 10,000 connections per square centimeter, each with a terahertz bandwidth. Massive low cost connectors improve usability of chips with lower component count and ease yield problems. Use of high performance AlGaAs semiconductors has been thwarted in electronic systems by an unfortunate combination of low yield and speed loss in the connectors. The ease of re-assembly of optically interconnected stacks allows independent redesign of various components of the computer for

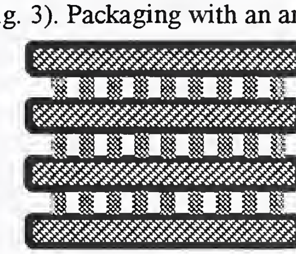

Figure 3. Three dimensional optical coupling between circuits with two dimensional VLSIO wiring.

improved architectures, rapid prototyping, and design repairs. The greater surface area of a three dimensional stack also allows better cooling of the devices. The lower density of components allows use of lower cost manufacturing techniques. With the reduced requirements of 1 to 3 micrometer linewidths, customer generation of unique hardware could be performed via post-processing in shops similar to photo-processors today. Unique hardware architecture could be acquired much as each user today acquires highly unique program environments and software assortments. With low cost distributed production, billion dollar capital plants are replaced by large numbers of vendors providing high performance customized architectures.

Although optical computing in the last two decades has classically used optics to image between arrays of logic, the approach taken here is more like that of standard VLSI electronics. The interconnections are between logic gates on a planar surface. But the connections with Very Large Scale Integrated Optics (VLSIO) use waveguides which have the properties of transmission lines rather than load lines used in today's electronics. Transmission lines require greater attention to reflections off imperfections and impedance matching (or reflectionless absorption at the intended receiver in the case of optics). Transmission lines naturally provide the highest speed transmission for a given length. The optical waveguide as a transmission line also removes capacitance as discussed before The use of waveguide transmission lines rather than the classical imaging approach of optical computing has several advantages (West). The average connection distance is 100 to 1000 times shorter using waveguides rather than lenses, reducing propagation delays (West). The reduced propagation delays are essential to retain the speed advantages of optics in serial computing. The manufacture of waveguides can be performed using the proven photolithographic techniques that created the electronics revolution In contrast, imaging systems require numerous expensive optical elements be reproduced for each processor In photolithography, the sophistication of the expensive optics at today's technology maximum resolution are used to project onto the patterned surface. The optics are then released to regenerate a new wiring pattern, often on the very same semiconductor surface. This amortization of the expensive capital plant over millions of processors is what makes computers cheap while the factory is very expensive Non-replicating optical imaging systems are contradictory to this manufacturing principle. Furthermore the use of waveguides to wire components allows greater complexity than the million or so isolated pixels allowed with today's lenses. The lens systems also image homogeneously. So more complex signal routing, required in any computer architecture, must be created by repeatedly splitting and recombining the image field in various parts. The repeated splitting with various combinations further expands the expensive optics requirements. Finally, components connected by waveguides can be placed at larger separations, not limited by the lens field of view. The temperature tolerance of the optical components has been a serious limitation in working devices and is easier to control with lower density components spread over several chips (West). In spite of these strong advantages, very little work is being conducted on VLSIO systems, most likely because of the extreme difficulty of the design of the necessary components and the primitive level of integrated optics.

The idea of integrating the optical components onto a single chip was first suggested by S. E. Miller (Miller). In spite of the offered promise of high density integration of optical components, two-dimensional lateral connectivity to date has nowhere approached that of VLSI electronics. The obstacle has been the incapability of guiding light with strong dielectric confinement due to the rapid increase in scattering with dielectric ratio. This scattering increases as a square of the difference in dielectric constant between guide and cladding, requiring the dielectric constants to remain within 1% of each other for a typical waveguide. (Deri). This requirement has caused the thickness of a

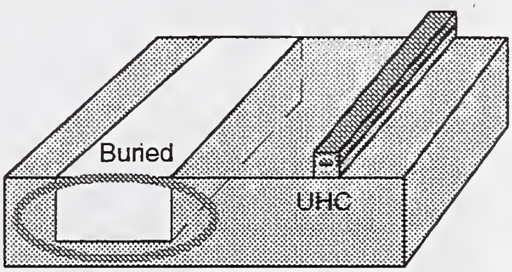

Figure 4. Note UHC waveguides have a mode area 20 times smaller than the typical buried waveguide.

typical waveguide to be larger than the free-space wavelength (Kogelnik). This larger dimension was also welcomed considering the fabrication capabilities at the time. The practical problem of scattering can be solved by the use of mid-infrared light because the scattering losses drop with wavelength to the third power (Marcuse). Ultra High Confinement (UHC) waveguides can be created with a high refractive index ratio between cladding and guide. Ultra High Confinement is defined here as confinement of light in a waveguide with an effective cross-section less than a tenth of a squared free-space wavelength or a resonator volume less than a cubic free-space wavelength (see Fig. 4). Because of the high confinement, a full vector field analysis of the mode is essential for accuracy. A practical implementation of an UHC waveguide in the mid-infrared region uses Ge with refractive index 4.0 on GaAs with refractive index 3.27 (Dubey). The Ge waveguide can be deposited on top of GaAs substrate via UHV E-Beam evaporation (see the next paper in this conference proceeding). Both the materials have excellent infrared and thermal properties and have almost perfect lattice matching. Any active material can be grown on the GaAs substrate before the Ge evaporation and interact with the strong fields at the Ge/GaAs boundary. An entirely new class of physical devices using the intersubband transition can be used for this mid-infrared interaction. The physical phenomena include lasing, modulation, detectors, second harmonic generation and other nonlinear interactions (Liu, Levine, and Andersson). The Ge/GaAs UHC waveguide geometry can scale to the near-infrared as lithography resolution improves to 0.1 μm with the use of GaAs with refractive index 3.6 as the waveguide on AlAs with refractive index 2.9.

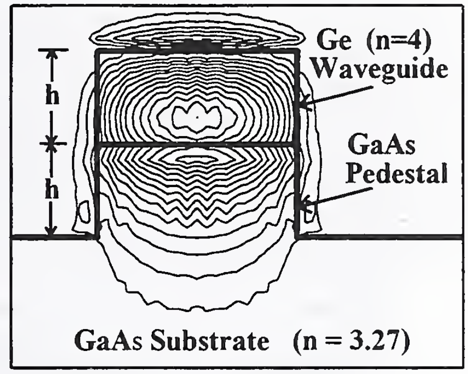

Figure 5. An UHC pedestal waveguide with vertical mode component.

Using the numerical analysis and microwave experiments we show that a large index ratio confines the light into a waveguide with dimensions a small fraction of the wavelength of light. Figure 5 shows the electric field profile for the vector component in the vertical direction. This vector mode profile was derived numerically using a custom finite element method (FEM) time domain program (Wojcik). An approximate mode was generated and propagated down the guide until steady state was achieved. The effective index of the mode was calculated from the linear phase shift with distance. This procedure was repeated for several ratios of waveguide height to free space wavelength. To test the new UHC waveguide properties, we conducted microwave scaled experiments. This scale testing is much in analogy to that of wind tunnel tests for airplanes. We purchase dielectric materials in the 4 GHz microwave region that have the same dielectric constant as Ge (4.0) and GaAs (3.27) with an accuracy of better than 3%. The microwave scaled waveguides are machined to a size of h=12.7 mm and width of 25.4 mm. Propagation experiments similar

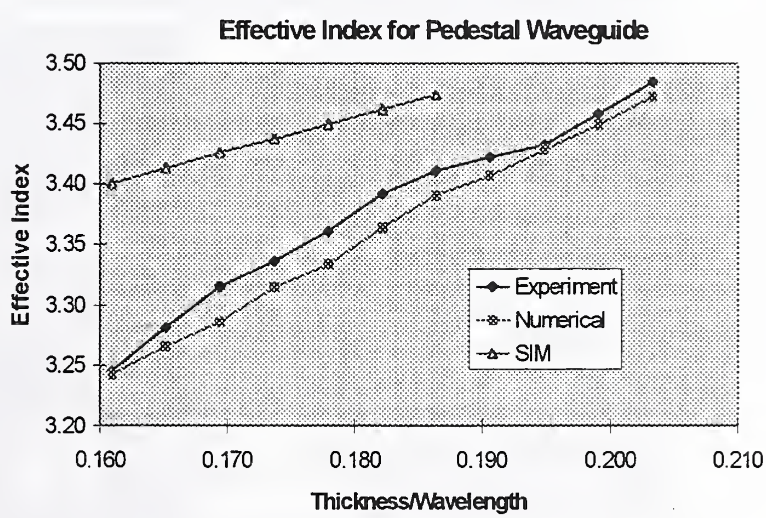

Figure 6. Theory (Spectral Index Method), Experimental (microwave), and Numerical (FEM) results for effective index. Note the numerical agrees well with the experiment, but not the theory.

to that of the numerical are performed on the real microwave guides and the effective index measured. Note the size scaling of the waveguide to the microwave for the optics is a perfect scaling. No effects are partially scaled. The results are shown in Figure 6. These results show good confinement ($n_{eff} > 3.27$) when h/λ is greater than 0.170. In practice, we use h/λ between 2.0 and 2.1.

Coupling into the UHC waveguides has been a major practical obstacle to their fabrication and testing. The buried waveguide mode has relative large size of one to three free space wavelengths that allows direct output from a cleaved edge. The UHC waveguide has a dimension that is about 0.2 by 0.3 free space wavelengths, which does not allow efficient coupling to air from the edge of the waveguide. A technique has been developed for robust coupling to these guides for a round Gaussian beam normal to the GaAs wafer surface. This coupling involves several steps, each using a sophisticated optical element. First, the UHC waveguide is adiabatically tapered from 3.7 μm wide rectangular mode to 13.5 μm wide slab mode over a distance of 40 μm. This wide mode is then scattered at a 21 degree angle into the substrate with a non-uniform, but periodic grating coupler. The teeth of the coupler are monotonically increased in scattering strength so as to radiate a Gaussian intensity profile with a diameter of 120 μm. The angle in the substrate is greater than the total internal reflection angle to ensure no radiation to the air side of the coupler. The highly elliptical spot size is then coupled to a round Gaussian profile beam with a diameter of 120 μm by use of an aspheric off-axis elliptical four level Fresnel lens on the back side of the substrate. All critical coupling steps of the interconnection are done at the lithography stage. The through-wafer alignment of the lens to the Gaussian coupler needs to be better than 1.0 μm to ensure < 10 % loss in efficiency. This alignment is performed by using a round Fresnel lens to burn a small alignment spot on the opposite side of the wafer with a CO_2 laser. Once the lens array is fabricated, the wafer has a good tolerance to misalignment. The angle of the input beam must be within 10 milliradians for high efficiency. However, semiconductor wafers are flat to within 10 μm and most large particles are less than 20 μm so a stacked cm square wafer will naturally be aligned to within 1 milliradian. The narrow 10 mrad acceptance angle in two dimensions filters out unwanted scattered light.

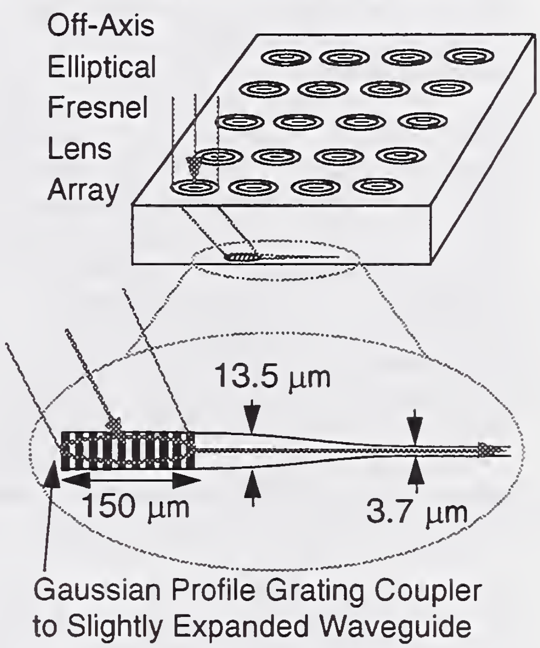

Figure 7. Coupling to UHC waveguide with a normal incidence 120 μm diameter beam.

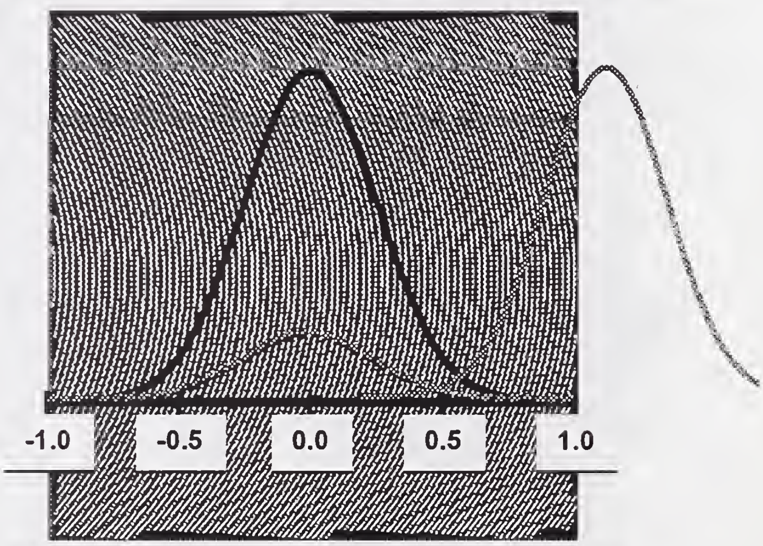

Figure 8. Off-Axis Elliptical Diffraction Lens with mis-aligned Gaussian beam shown as a function of beam diameter.

The 120 μm diameter mid-infrared beam can propagate 2 mm in free space without diffracting, allowing wide tolerance in spacing of the chip stack. The lateral mis-alignment of the Gaussian beam causes loss of efficiency. The large size of the diffraction lens improves the tolerance to lateral misalignment and particles on the surface. However, too large a lens reduces the number of couplers per square centimeter. A good compromise is the 120 μm diameter beam and a 180 μm diameter lens allowing 3000 couplers/cm^2 to be created. The diffraction lens has less acceptance area than indicated by its aperture. This is because the coupling to the UHC waveguide requires single mode input. A lateral misalignment only couples to the extent the beam it has a component with the centered Gaussian beam (see Fig. 9). Note a 20 μm lateral mis-alignment for the 120 μm diameter beam causes a 10 % loss in coupling. However, a noise source at the correct angle and beam profile but separated by 120 μm only has a 3% coupling. A wrong angle or beam profile typical of noise has very low coupling. The strong single mode nature of this coupler naturally excludes noise, effectively creating a 'pipe' for the light. However, the tolerance of this coupler is well adjusted to that angle and position which are reasonable allowable for stacks of wafers.

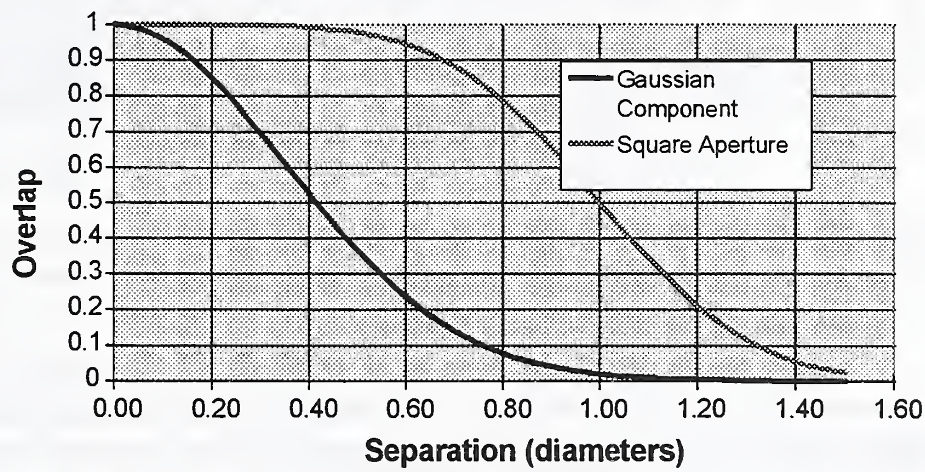

Figure 9. Loss of coupling with lateral misalignment of the diffraction lens. The lens aperture is actually that of the Gaussian beam overlap, not the visible square.

The line focus Gaussian beam must couple efficiently into the waveguide. Normally, a uniform periodic grating coupler limits the efficiency of the coupling to less than 80 % at best, with actual couplers much lower. The large 10 μm wavelength allows non-periodic grating couplers to radiate a profile more of a Gaussian than a decaying exponential for improved efficiency. A preferred method would keep the tooth depth constant and vary the width that is easy to fabricate with standard lithography. After extensive effort, we found that the very large coupling variation needed required at least two etch depths for sufficient range of tooth coupling. The current design uses 33 teeth with a 4.5 μm period and two masks with etch depths of 0.2 μm and 0.45 μm. The design started with the measure of single tooth scattering coefficients for transmission, reflection, and scatter, including phase shifts for a number of different teeth. The transmission phase variation was used to vary the period slightly to get a uniform scattered phase. After completion of the design from these single tooth parameters, the total Gaussian coupler was then modeled with the Finite Element Method in two dimensions for a slab waveguide. The output of this coupler was measured for

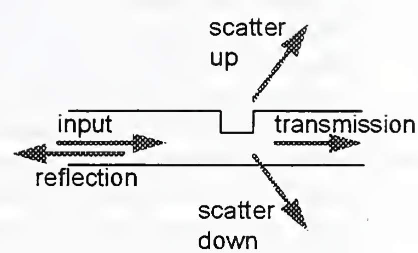

Figure 10. Single tooth model for calculating coupling coefficients.

Gaussian diameter and overlap. The final design had a Gaussian overlap into the desired beam of 85 %. The losses were from scatter to air, backwards scatter down the waveguide, backwards scatter at -21 degrees into the substrate, uncoupled transmission in the waveguide, and non-Gaussian components of the scattered beam. Each of these scatter losses are less than a few percent. The coupler attempted to use only a tooth width near that of a half wave in the waveguide. This was because the 1.5 μm width was easy to fabricate, and the single tooth has minimum back scatter down the waveguide for this width (see Figures 11 and 12). The taper has a 98 % efficiency as modeled by the Finite Element Method.

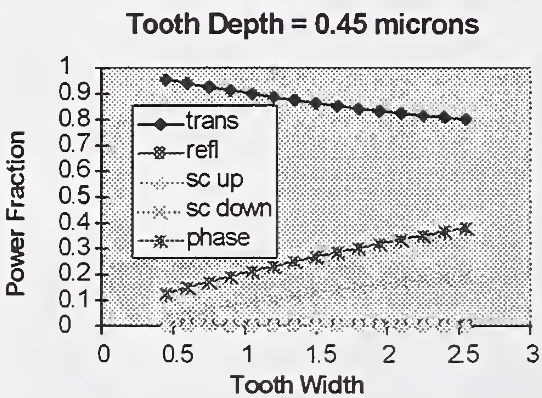

Figure 11. Single tooth transmission, phase shift, and scatter to the substrate for a 0.45 μm depth.

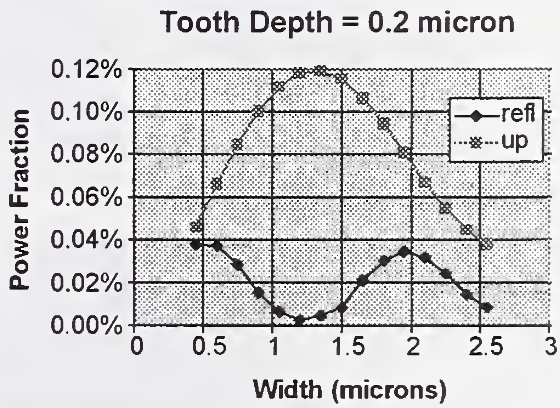

Figure 12. Single tooth reflection and scatter to air expanded for the 0.2 μm deep tooth.

One of the biggest advantages of the high index of refraction is the ability to create waveguide bends with a radius of less than one free space wavelength. Both FEM modeling and microwave experiments show that a right angle bend with a radius of 7.5 μm for 10 μm light has a 90% efficiency single mode transmission. This tight bend allows creation of dense components for VLSIO (see Fig. 13).

The UHC waveguide has several advantages in opto-electronic device improvement due to its small size. The UHC waveguides are capable of creating resonators with volumes less then one tenth of a cubic free space wavelength. This is 1000 times smaller than VCSELs. The 20 times smaller beam diameter improves gain and other optical properties by a similar factor. The capacitance of the devices is also much reduced, improving the bandwidth of opto-electronic devices by more than a factor of 10 over buried waveguides, nearing 1 THz in frequency response. For example, modulators created with UHC resonators for the mid-infrared are predicted to have 3 fF capacitance and less than 7 fJ time-power product. As the UHC waveguides are scaled 10-fold smaller to the near-infrared with improved lithography, these numbers are lowered 100 fold. It should be noted however, that 1.0 micrometer resolution lithography is barely adequate for the sophisticated elements discussed here, even though our wavelength is 10 microns. For instance, the tooth width shown in Figure 12 must vary from 0.9 to 1.8 μm with 0.1 μm precision. This capability is just possible

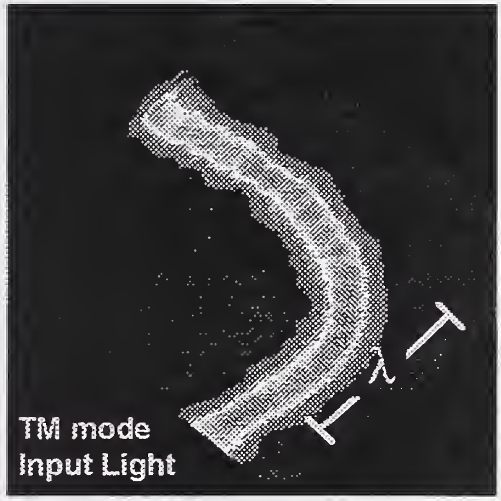

Figure 13. A cross section of the field of a pedestal waveguide mode propagating around a 7.5 μm radius bend.

with 1.0 μm linewidth lithography, ten-fold smaller than the free space wavelength. Similar requirements are seen for most all our components. As such, near-infrared use of UHC concepts will not be viable until the availability of 0.1 μm linewidth lithography. However, highly useful components can be created in the mid-infrared today which will develop the UHC integrated optics.

This development of UHC waveguides for VLSIO is at its beginning, but showing good promise for providing optical components with the same density as current electronics. Furthermore, it is possible using the components illustrated here to create fully three dimensional computer systems with high connectivity and reasonable tolerances for fabrication and packaging with position and angle. We also show that UHC waveguides can connect in a two dimensional plane at compact sizes which allow very much improved opto-electronic performance, leading to true terahertz technologies.

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Challenges in Optoelectronic Packaging

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Over the last 10 years, optoelectronic components have developed at a rapid pace. Very high performance components were successfully introduced in long haul communication links. These systems share the common characteristics that the price of the components is distributed among a large number of users. Recently, new volume applications have appeared that are extremely sensitive to the price structure. These applications have stressed the importance of packaging to reduce the final cost of the products. For instance, in the area of consumer electronics, new packaging techniques have led to the integration of microcomponents such as microprisms and lasers to form an extremely compact read/write head for CD players, at an appreciable size and cost reduction. Optical data storage, display technology, printing and copying, parallel data links, are other areas with tremendous market potential that can immensely benefit from advances in the optoelectronic packaging area.

Packaging cannot be an after-thought. It has to be an integral part of the device design, from inception to completion of the optoelectronic module. Many of the optoelectronic envisionned applications require the use of parallel channels, and the alignment of waveguides (or fibers) with lasers and detectors. Techniques such as silicon waferboard, where a silicon wafer is used for mounting different optoelectronic components, is a very promissing approach for implementing optoelectronic modules. Etched features in silicon can be used to align different components. These features include alignment pedestals and fiducials, V-grooves, and pyramid-shaped pits.

The new challenge involves developing approaches for accurate placement and mounting of optoelectronic components onto a module. One key requirement is the precise aligment of optical fibers to lasers. For short distances, multimode fibers and vertical-cavity-surface-emitting lasers (VCSELs) can be used. Because of the low divergence of the beam coming out from VCSELs, very high coupling efficiencies to multimode fibers can be obtained. Major companies (Motorola, Hewlett-Packard, AT&T) are presently following this approach for parallel data links. On the receiver side, light is reflected at the end of an angled polished fiber, a gold coated V-groove, or an angled-etched polymer waveguide, onto an MSM detector. The transmitter and receiver module are connectorized. Hermiticity of the whole package, laser reliability, modal noise are key issues. The real challenge in this approach is to assemble and manufacture a low-cost parallel data link. For longer distances applications at high data rates, single mode fiber and single transverse mode optoelectronic components will be required. Some of these applications might require the multi-access capability of optics. Wavelength-division multiplexing might be an appealing approach. One of the challenge here is to efficiently couple light from a single mode laser to a single mode fiber or waveguide. Passive alignment technique based on V-grooves or flip-chip bonding are appealing. But many problems remained to be addressed. Mode

transformers and large mode devices designed for efficient and ease of alignment to single mode fiber/waveguides are very active areas of research.

As new applications appears, new devices will be developed. As the complexity of integration progresses, new challenges in packaging will surface. In the end, the real challenge for optoelectronic technology will be to develop the manufacturing, packaging and automation technology for producing a high quality product at a competitive price.

Challenges in Optoelectronic Packaging

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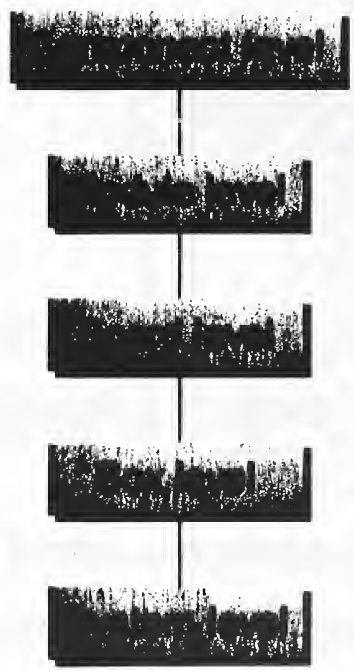
Applications of OE Packaging Technology

- Communication Links
- Data Links
- Optical Data Storage
- Display Technology
- Printing
- Copying
- Entertainment

Optoelectronic packaging heirarchy



ICs,OEICs,
discrete devices

Electronic MCMs,
Si waferboard

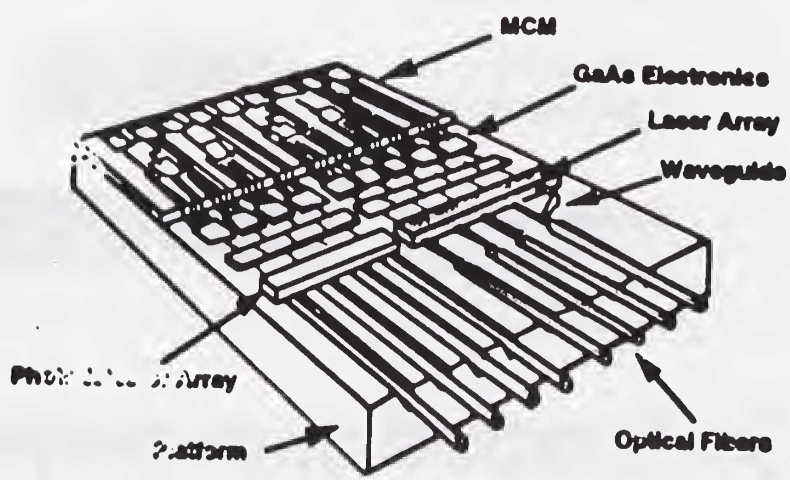
Printed wiring board,
Optical waveguide

Optical/electrical backplane
optical waveguides

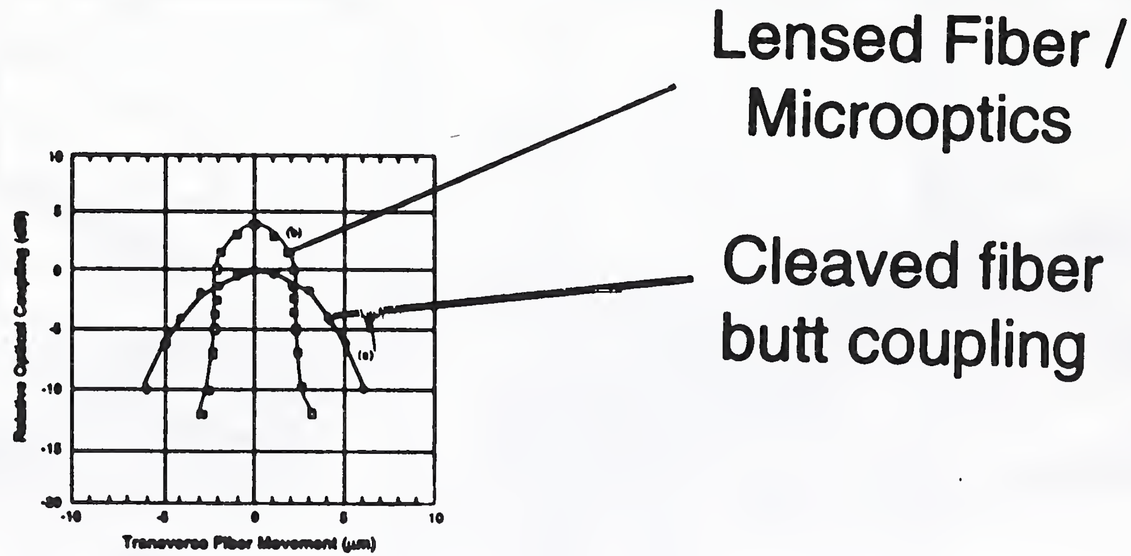
Time Division Multiplexing
Wavelength Division Multiplexing
Space Division

Optoelectronic modules

- Module for hybrid integration of Si/GaAs electronics, laser emitter arrays, fibers and photodetectors
- Possibility for passive alignment with V-grooves etched onto the platform
- Silicon is becoming the choice material
- Groups involved : AT&T, GTE, GEC-Marconi and BNR-Europe



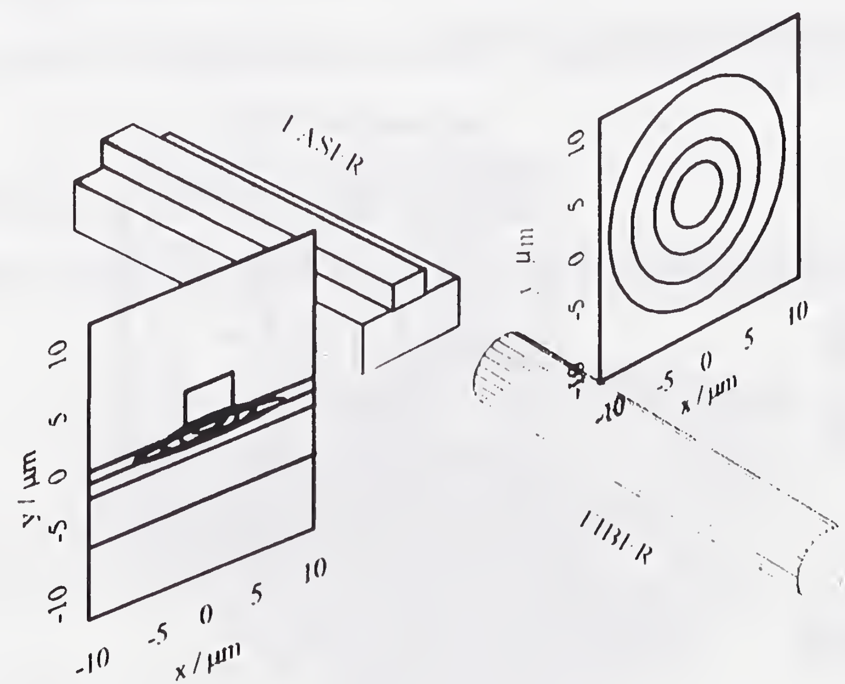
Alignment tolerances



AIM: To optimize rather than maximize the coupling efficiency with the cost, reliability and performance contstraints imposed by the application

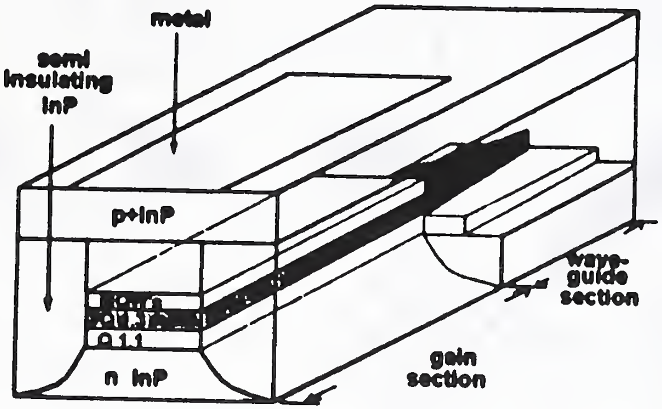
Photonics Switching Laboratory

Fiber- laser mode mismatch

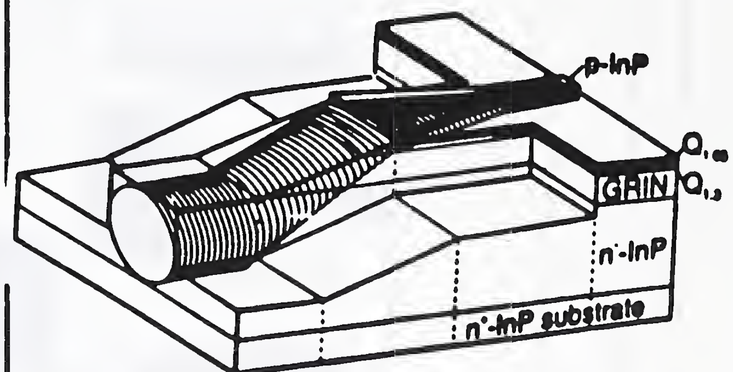


Integrated Optoelectronics Laboratory

Mode expanders - Examples

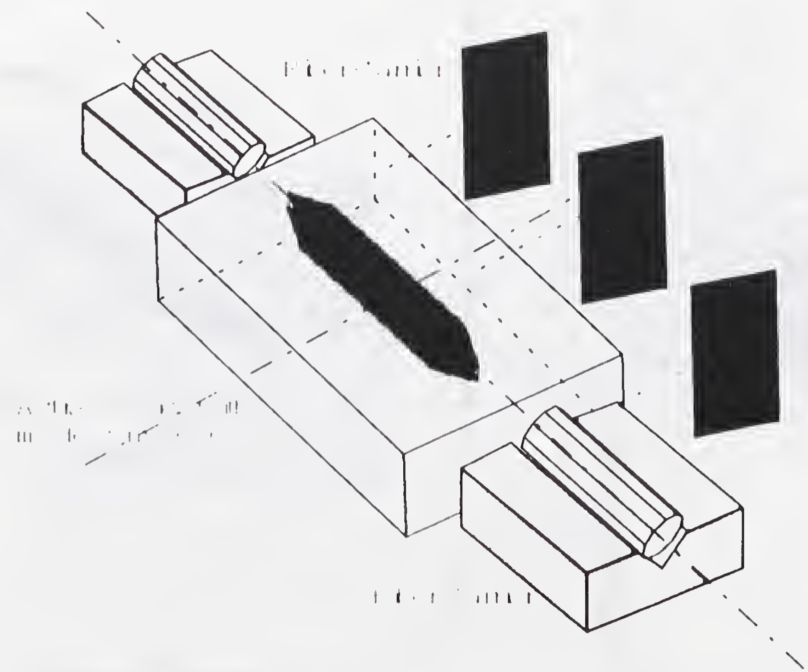


Lateral taper



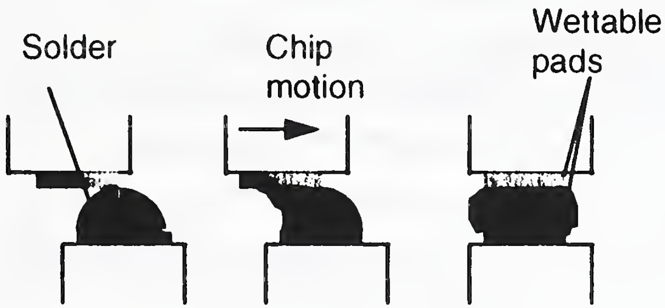
Vertical taper

Mode expanders

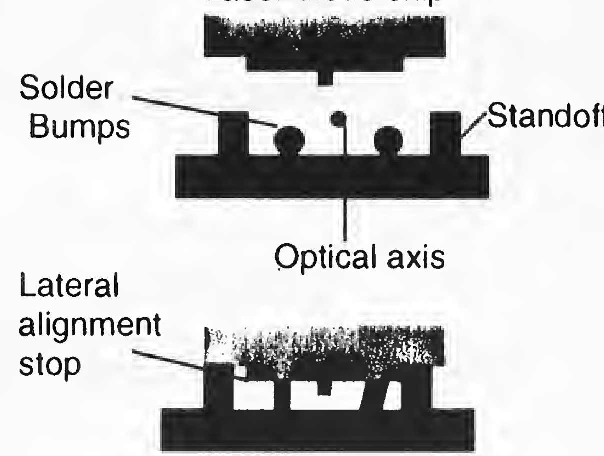


Integrated Optoelectronics Laboratory

Alignment control techniques



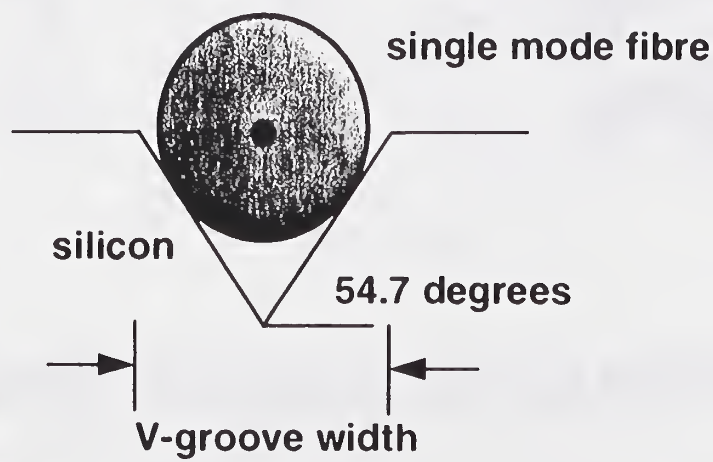
Solder self-alignment



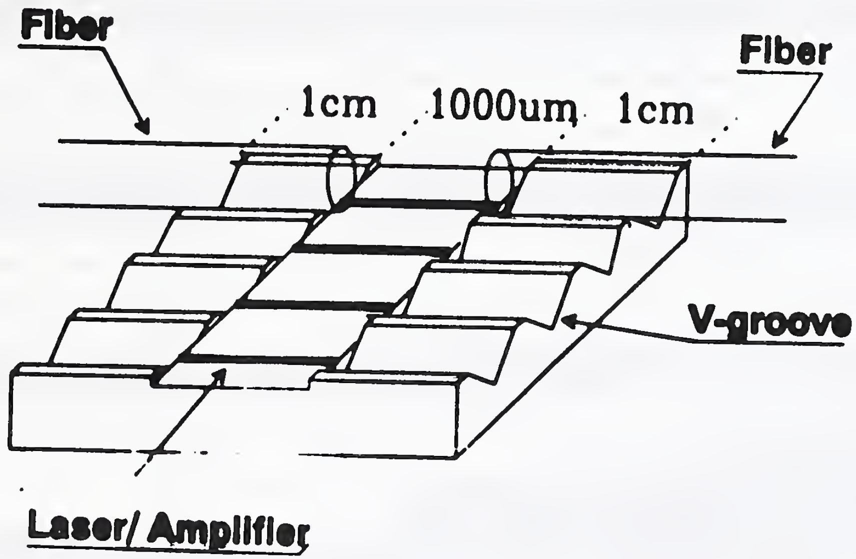
Alignment with mechanical features

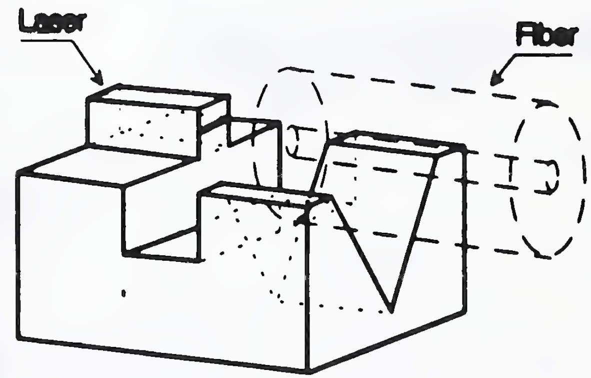
Fiber Placement in Silicon V-Grooves

- V-grooves are used to accurately position optical fibers
- V-grooves are created with preferential etchants



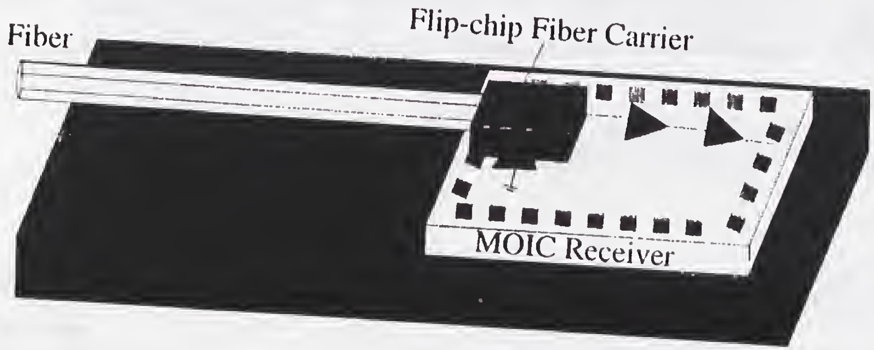
Passive alignment schemes





V-grooved passive alignment scheme for coupling
from fiber to laser or amplifier

Work at UM - Photodetector packaging

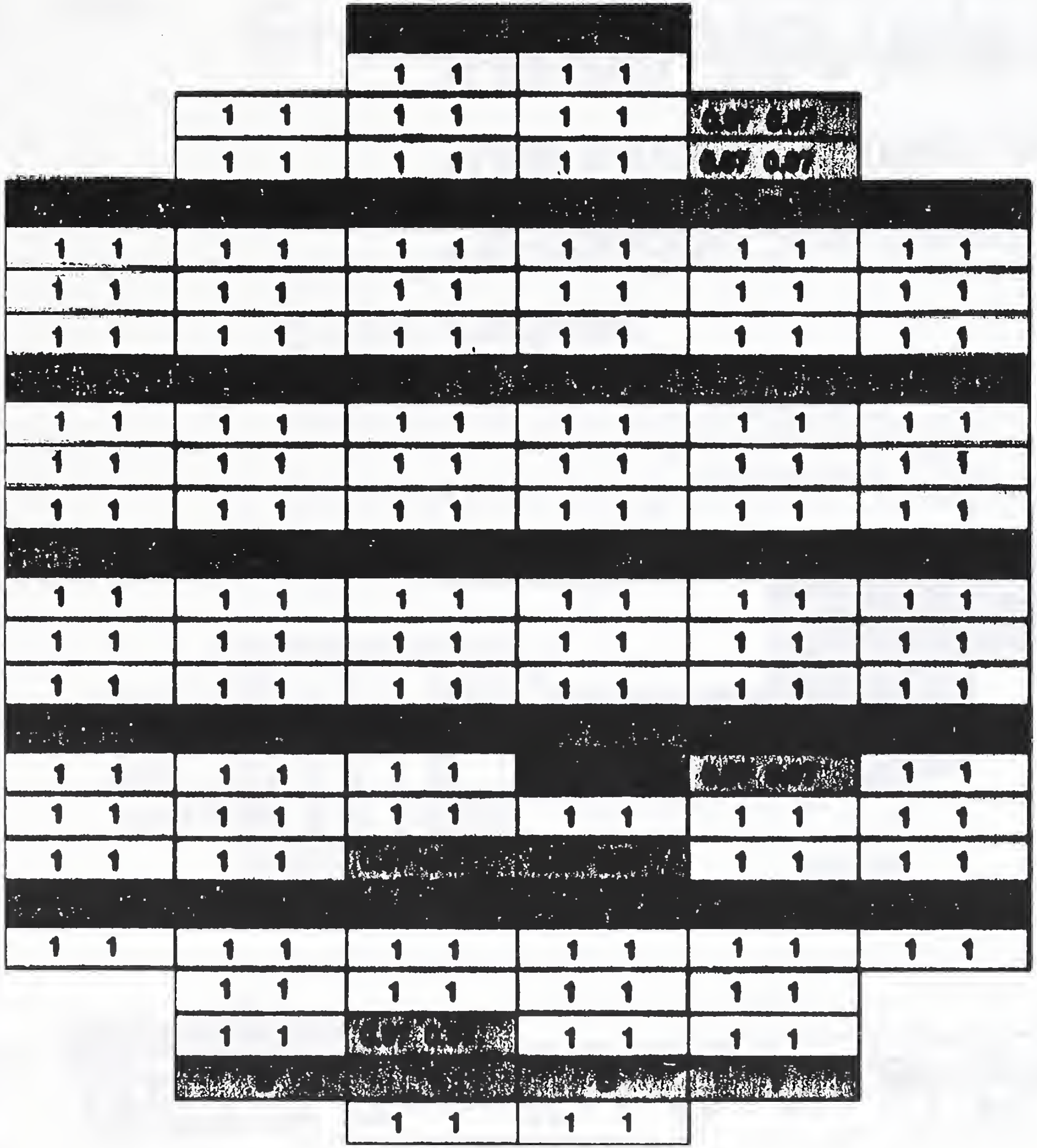


Approach 1: Reflection off V-groove end

Approach 2: Reflection off angle-polished fiber

Integrated Optoelectronics Laboratory

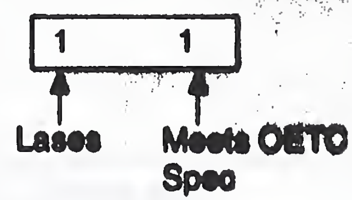
3" Diameter MOVPE-Grown OETC VCSEL Wafer Yield at 25°C



OETC Laser Yield = 99.8%
Full Array Yield = 94%

108 (34 x 1) array chip tested
3672 lasers tested

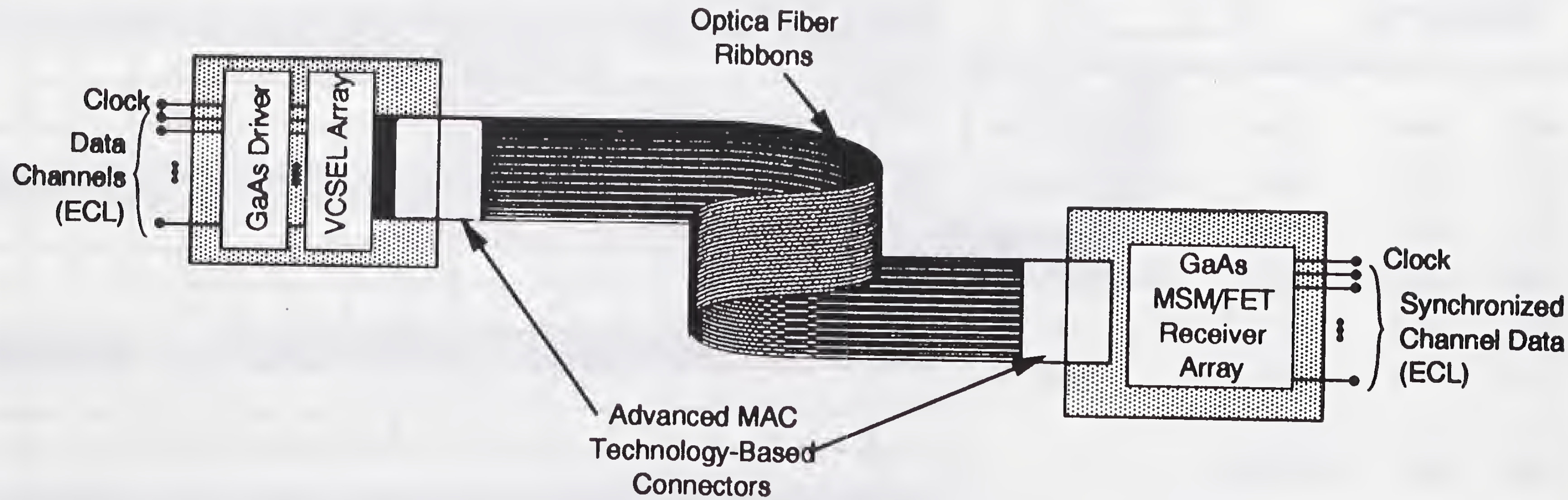
	Average	Max	Min	Avg Array Std. Dev.
I_{th} (mA)	3.07	4.75	2.25	0.223
V_{th} (V)	1.59	1.75	1.54	0.012
Rd op (ohms)	34.00	44.00	29.51	0.669
P @ 10 mA (mW)	2.07	2.44	1.28	0.171
V @ 10 mA (V)	1.82	2.08	1.76	0.006
lambda (nm)	843	858	824	3.685



T = Test Chip
D = Discrete laser chip

Honeywell

OETC Parallel Optical Data Link



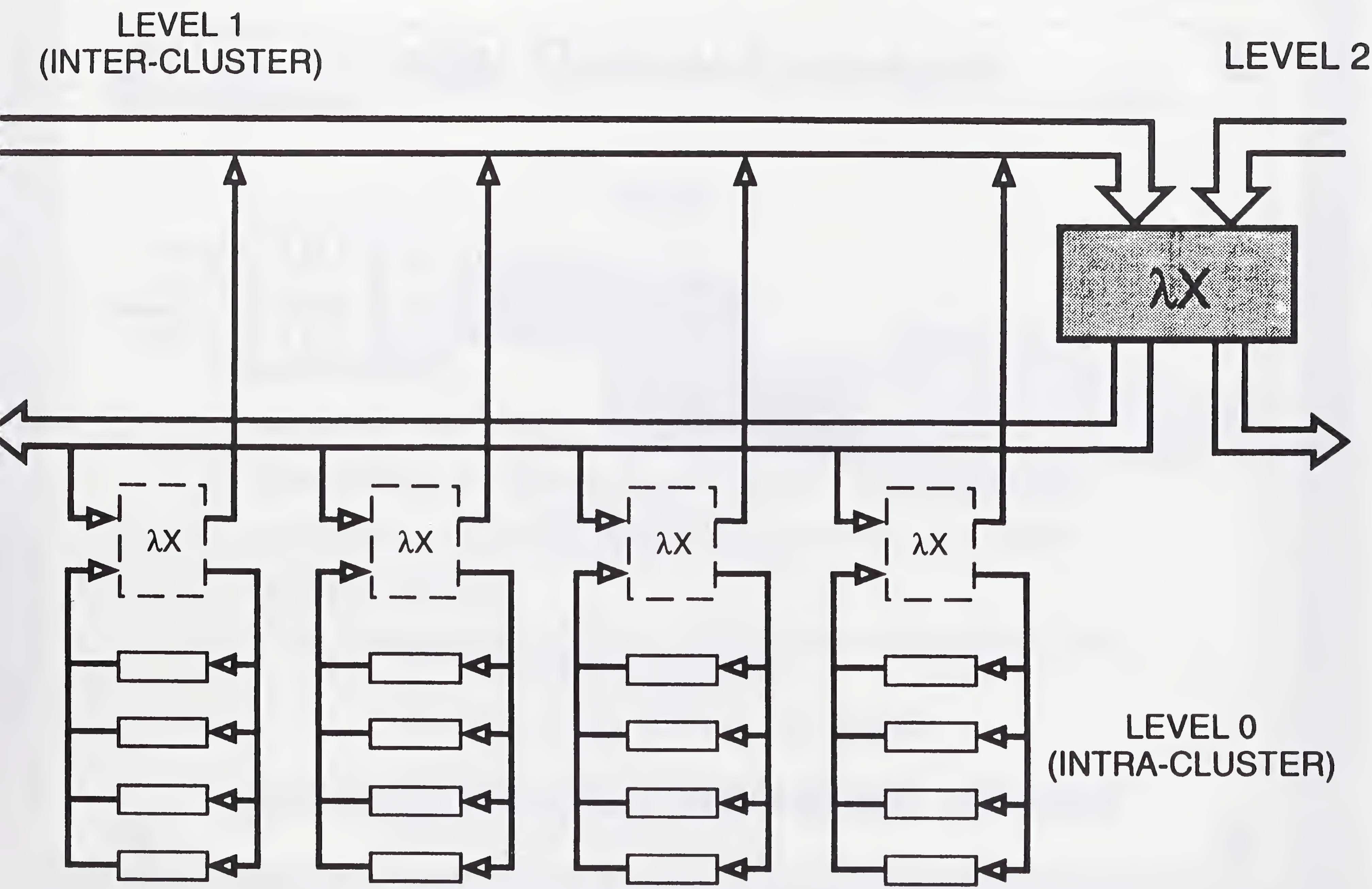
Features:

- 32-channels - array based
- Data bandwidth 500Mb/s per channel
- Line pitch - 140μm per channel
- Data transfer latency <2ns

STA30382RAM005

Present parallel data links -Issues

- Low cost components : connectors, detectors and lasers
- Alignment between active and passive devices
- Waveguide technology : polymer, glass etc.
- Hybrid packaging technology (GaAs / Si)
- Hermeticity
- Laser reliability - VCSELs
- Link noise : modal noise



LEVEL 1
(INTER-CLUSTER)
LEVEL 2
λX
λX
λX
λX
λX
LEVEL 0
(INTRA-CLUSTER)

Advanced Optoelectronic Manufacturing Technologies

White Paper; presented to NIST/ATP

Hsing Kung, Ph.D.
Vice President, Manufacturing
SDL, Inc.

1.0 Introduction

SDL, Inc. proposes to form a consortia of U.S. industry leaders in optoelectronic device and equipment manufacturing to dramatically advance the state-of-the-art manufacturing technologies available to the US optoelectronic industry. The goal of the consortia is to both develop and demonstrate in a manufacturing environment, production technology and tooling resulting in dramatic manufacturing advancements as realized through low cost, high volume, precision optoelectronics manufacturing. The proposed program will result in the following:

Establish high volume manufacturing of optoelectronic components in the U.S.
Dramatically reduce the cost structure of sophisticated optoelectronic components by a factor of 5 to 20x.
Result in a total component market cost savings of greater than $100M
Solidify the U.S. position in optoelectronics based systems; markets that exceed $200B.

The impact of the proposed program will specifically address the optoelectronics markets of telecommunications, printing, and optical data storage. In addition, the specific issues to be addressed in the manufacturing technologies will enable low cost manufacturing in a flexible manufacturing line. As a result, the benefits that are realized in the high volume markets of telecommunications, printing and data storage will be realized in many other smaller markets including medical applications, environmental monitors, satellite communications, industrial machining, and many others. The establishment and solidification of a strong manufacturing presence in the optoelectronics field is critical to maintaining on-shore supply of component technology. More significantly, as has been shown in other technology areas, in order for the optoelectronic based systems market to maintain a strong presence in the U.S., the component supply must be manufactured on-shore or at a minimum, by U.S. based organizations.

The proposed program to advance the state-of-the-art in optoelectronics manufacturing capability includes:

Manufacturing technology development in the areas of assembly, packaging and testing.
Advanced device/package design that further integrates functionality on to the semiconductor chip.
Demonstration of low cost, high volume manufacturing line as addressed to the markets of telecommunications, printing , and data storage.

The following sections discuss some of the issues to be addressed in the proposed program.

2.0 Optoelectronic Manufacturing

The manufacture of optical and optoelectronic devices in III-IV materials generally consists of epitaxial growth, wafer processing, device assembly, package assembly, and testing. U.S. manufactures have managed to remain competitive by having state-of-the-art facilities in the first two areas of manufacturing, growth and processing. Unfortunately, the majority of the manufacturing costs for the volume manufacturing of these components is contained in the later production steps, in which U.S. industries are far behind their Asian and European counterparts. Table 1 summarizes these manufacturing steps and comments on the technologies involved. To address these competitive disadvantages, SDL proposes industry teams which concentrate on those areas of assembly, packaging and testing which are most deficient in the U.S. industry

Table 1

Optical Component Manufacturing

Manufacturing Step	Present US Industry Competitiveness	Relative Manufacturing Cost of Manufacturing Step
Epitaxial Growth MBE or MOCVD crystal growth of the active material in the optical device	Excellent	5%
Wafer Processing Photolithography, implants and metal depositions required for device fabrication	Excellent Large infrastructure of the US silicon industry directly applicable to these manufacturing steps	10%
Assembly Die bonding and wire bonding for preliminary device evaluation	Average Much of electronic hybrid assembly equipment applicable, but no volume assembly equipment available for optical devices	20%
Packaging	Poor Generally good technology without volume; manufac-turing equipment in place	40%
Testing Measurement of key parameters required before shipping	Very Poor Only a small amount of custom in-house equipment available	25%

3.0 Technology Programs

A variety of technology programs to address volume manufacturing needs in the assembly and testing of advanced optical components will be proposed. These programs should be a combination of design innovations that allow more cost effective manufacturing and equipment automation for reduced unit cost in key assembly and test processes. The following are examples of what will be proposed.

3.1 Advanced Silicon Optical Bench Assemblies

This novel manufacturing architecture is to combine multiple active and passive optical and electronic components on a common silicon carrier. This architecture will allow well developed automated pick-and-place assembly developed in the IC industry to penetrate

optical manufacturing. This proposed carrier can easily incorporate micron accuracy, machine recognizable registration marks required for automated assembly. In addition to serving as the common carrier, the optical bench can incorporate active functions suitable to silicon technology. Examples include power monitoring, electronic driver circuitry, and optical power feedback loops. The integration not only eliminates the required assembly of discrete components and .but also utilizes high volume, low cost silicon process technology. In addition, this architecture allows wafer testing capability. All the above factors can significantly reduce manufacturing costs by a factor 5 to 20x.

Two major areas of development need to be focused on for this technology program:

1. Components manufacturers need to develop key technologies to design and assemble both active and passive elements on silicon benches (wafers). For example, fibered laser products must develop i) laser die attach process on silicon, ii) lens alignment process on silicon, or iii) fiber alignment process on silicon and others.

2. Semiconductor equipment manufacturers need to modify existing equipment and technology to accommodate silicon bench processes. For example, silicon benches may have non-planar surfaces. The automated pick-and-place machine may need to have its holder design modified to accommodate the non-planar feature.

3.2 Fully Automated Testing

The second highest cost component in optical device manufacturing is acceptance testing. For the testing of optical components, parts handling is an area requiring substantial development. Presently in the U.S., the test equipment utilized is only partially automated with manual handling of individual parts required. This can be automated with robotics controlled loading of individual parts, or alternatively manual loading of large batches of parts.

3.3 Manufacturing Control Software

Process controls directly impact yield and product quality. At present no software control system has been developed to deal with the complex interdependence of wafer process yields, individual component test data and manufacturing costs. Software can be developed with the following capabilities:

Contain tacking data for each wafer, component, and assembly for complete traceability.
Contain process control data from key identified process steps.
Apply standard statistical process control (SPC) to identified processes.
Contain serialized (or batched) test and burn-in data for all components.
Correlate test data to process control steps.
Provide yield information against defined specification for each process and product.
Utilize yield to monitor manufacturing costs.

4.0 Impact of Improved Optoelectronic Manufacturing on Key Industries

4.1 Fiber Optic Communications

Fiber optic communications encompasses markets ranging from long haul telecommunications and local area networks to cable television. Increasingly, the distinction of these markets is becoming blurred by the general requirement for generic high bandwidth data communication. The world market for optical communications is presently estimated at over $3B and expected to rise to $11B by 1998, making it the fastest growing segment of the electronics industry. This dynamic growth will be realized only through the availability of price competitive technology. At the component level, low cost and high performance optical transmitters, amplifiers and receivers are critical to enabling the realization of these market growths.

Optical transmitters of today generally consist of a laser diode, electronic driver circuit, power and temperature monitoring and control in a compact fiber coupled package. In volume, these modules presently sell for prices ranging from many hundreds to many thousands of dollars. To meet market demands of the local area networks, the same basic functionality must be met at $10 to $20 per module. This price reduction of greater than 10X must be driven by a combination of technical innovations that simplify the components and well executed volume manufacturing.

Critical to these markets is the development of low cost assembly and in particular low cost fiber coupling. In today's technology, the fiber coupling is accomplished by a time consuming *active* alignment process. The silicon optical bench suggested in this white paper holds the promise of fast and accurate *passive* coupling of the device.

4.2 Laser Printing

The laser printing market place encompasses two distinctly different markets. The low power electrographic market serves laser printers and related computer and communication peripherals, such as for printers and color printers. It is characterized by established overseas competition at the component level, high established volumes, and the need for extremely low prices. This market strongly overlaps the data storage market. The low power electrographic market contrasts sharply with the substantially higher power thermal printing market, which serves primarily the direct-to-press and pre-press printing and publishing industry. This latter "high power" marketplace is presently emerging and both media and laser sources are in some stage of development. Sources for this very international market have been pioneered by U.S. industry in general, and SDL, Inc. in particular. This is a market place where the U.S. is in a strong position to extend and solidify it's leading position.

Both the electrographic and thermal printing markets have the capability of sustaining annual single source component sales levels in the $25M to $50M levels, although the

price-volume makeup is very different for the two marketplaces. The integrated systems businesses that these sources enable enjoy annual sales in the tens of billions (electrographics), or billions (printing and publishing) of dollars.

The major enabling technical leverage that this proposed program provides to both laser printing market places is lower cost of manufacture. In the low power electrographic printing market place, operating power levels leave packaging costs relatively less important. The impact of developing the silicon bench architecture will provide major strategic cost advantages in this market.

SDL has pioneered the development of advanced performance and shorter wavelength visible low power chip devices. When combined with enabling low cost, high volume silicon bench technology, this previously established market place can be significantly penetrated. Ultimate unit cost targets in this market are a fraction of a dollar at annual unit volumes of tens of millions.

Due to significantly higher operating power levels and power dissipation levels in thermal printing lasers, subsystem integration, assembly (packaging) and automated testing will have relatively higher impact of cost reducing these thermal printing sources. These sources typically require sophisticated optical lensing or alignments and this technology remains a dominant cost driver. This is not to diminish the import of the silicon bench architecture as a significant part of this cost improvement. Pricing goals in this marketplace are varied, as package architectures vary. Price goals can be tens of dollars in quantities of several hundred thousand units per year to hundred dollar price goals in quantities of tens of thousands of units per year. Performing sophisticated packaging in a cost effective manner with only moderate (10,000 - 100,000) annual markets is key to dominating this marketplace.

4.3 Optical Data Storage

The optical data storage market encompasses a growing number of applications that range from compact disk players, digital video disks, to CD-ROM. Primarily, optical data storage is based on a read only memory format, but more recently, systems that are based on higher power laser sources and magneto-optical disk media are capable of read/write data access. The driving technology of the optical data storage system is the ability to manufacture low cost diode laser sources. In addition, the ability to generate shorter wavelength emission from the diode laser source greatly impacts the volume of information that can be accessed on a given disk. The current manufacturing volumes for diode lasers for optical data storage exceeds 10M units a year. Currently, SDL is the only U.S. manufacturer of diode laser sources in the optical data storage field while the bulk of the manufacturing of laser diodes is in Japan.

Optical data storage is an excellent example of why component technology needs to remain in the US. In the area of data storage, the U.S. has maintained a technological advantage in the manufacturing of magnet disk based systems. As a result, the computer

industry has benefited from the on-shore supply and manufacturing of magnet storage systems, and it is quite evident that the only reason that the U.S. has a lead in computer systems sales is that the magnet disk and the microprocessor, the two most sophisticated technologies utilized in the computer, are manufactured on-shore. In the case of optical data storage, with the exclusion of SDL, no supply of low cost diode laser manufacturing is available. As a result, nearly all of the optical storage systems are manufactured in Japan. (Some systems are manufactured by IBM and Kodak; however, their combined market share is less than 5%.) As the optical data storage systems become increasingly more important in computer and display systems, the Japanese gain a distinct advantage in the systems market as a result of their components manufacturing capabilities.

Although the U.S. has fallen behind in the manufacturing of high volume, greater than 1M/year, the U.S. and SDL in particular have a distinct advantage in the technology used to fabricate short wavelength laser diodes. SDL is the leader in the manufacture of 630 nm laser diodes, in that the lifetimes and available power levels exceed that of foreign suppliers. In addition, SDL has demonstrated that in the area of chip manufacturing, SDL is price competitive with foreign suppliers. However, in the area of package assembly, the Japanese manufacturers have a distinct cost advantage.

The proposed program intends to advance the manufacturing capabilities for high volume laser diodes by developing automated die attach equipment, advanced submount designs, and automated testing equipment thus complementing the already existing volume chip manufacturing capabilities at SDL. The goal of the program is to demonstrate cost competitive units in a volume manufacturing line of 630 nm laser diodes for optical data storage.

4.4 Flexible Manufacturing

As briefly mentioned above, the issues that are being addressed for the manufacturing of components in the telecommunications, printing , and data storage areas will be implemented in a manufacturing line that is compatible with a wide variety of applications. The advantage of the optoelectronics technology, similar to that of Si integrated circuits, is that the differentiation of components for various markets is almost entirely contained within the semiconductor chip. As a result, advances in the assembly and packaging areas apply directly to all optoelectronics components. It is the goal of this program to insure that the advances that are made when addressing the primary markets will significantly benefit all other markets addressed by optoelectronic technology.

5.0 SDL Capabilities

SDL is the recognized world leader in advanced optoelectronics technology, as reinforced by numerous commercial technology awards. Historically, SDL has been the pioneer of high power laser diodes that address markets including thermal printing, telecommunications, satellite communications, industrial and scientific applications, environmental monitoring, and many others. More recently, SDL has entered the business

of volume manufacturing of laser diodes. Particular product lines have demonstrated market acceptance in both the data storage markets and alignment markets. Particularly noteworthy is that SDL is the only supplier of laser diodes for data storage in the U.S., and that SDL has proven to be price competitive with Japanese manufacturers such as Sony in the field of volume chip manufacturing for alignment systems.

As a result of SDL's technology lead, experience in volume manufacturing, and breadth of market impact, SDL is the only U.S. optoelectronics manufacturer that can fully realize the benefits of advanced optoelectronic manufacturing capabilities.

ADVANCED OPTOELECTRONIC MANUFACTURING TECHNOLOGIES

Hsing Kung, Ph.D.
VP, Manufacturing

SDL, Inc.

- *Optical Component Manufacturing*
- *Technology Programs*
- *Impact on Key Industries*
- *Summary*

SDL

SDL, INC. - COMPANY BACKGROUND

- *World leader in semiconductor laser technology*

- *World leading high power semiconductor laser manufacturer*

- *Complete vertical integrated manufacturing line at San Jose, CA facility*

- *More than 200 products, including:*
    - *CW laser diodes*
    - *CW single mode laser diodes*
    - *CW high power linear arrays*
    - *QCW linear arrays and stacked arrays*
    - *Laser diode drivers*

- *Serves rapidly growing telecommunications, medical, machine tooling, printing and HDTV markets*

SDL

U.S. COMPONENT MANUFACTURING

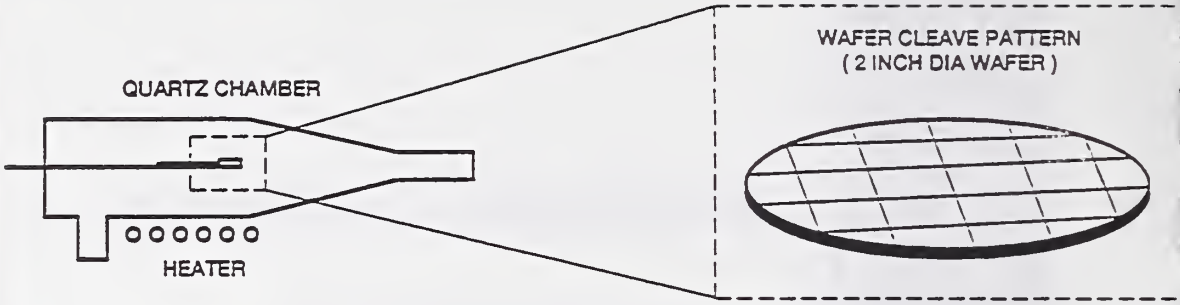
STRENGTHS

- *Leading technology*
- *Flexible manufacturing*
- *High performance and reliability*
- *State-of-the-art facility and equipment*

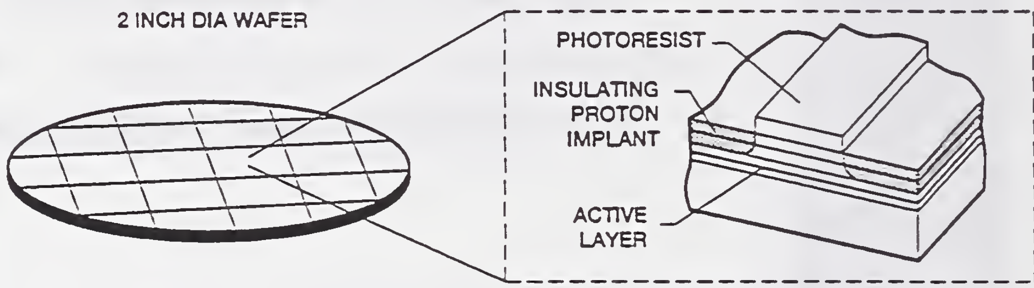
AREAS FOR IMPROVEMENT

- *Low cost manufacturing technology*
- *High volume manufacturing technology*

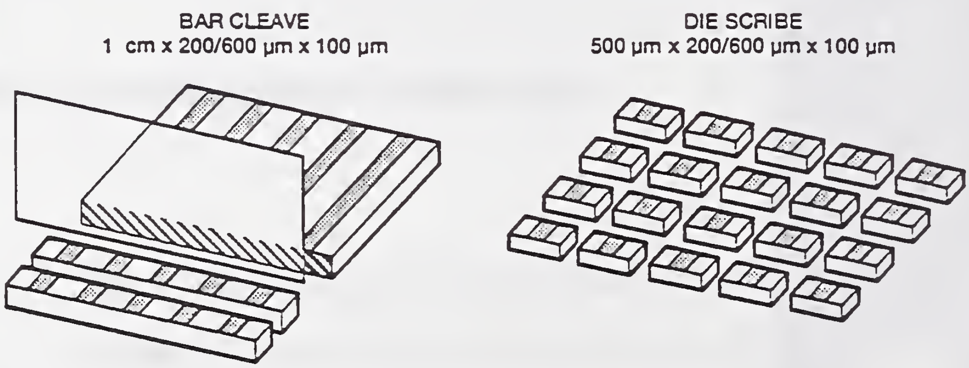
Layer Growth



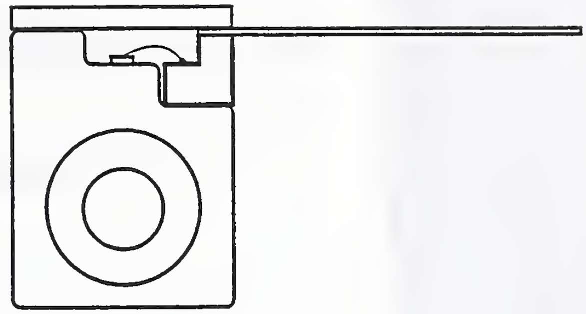
Wafer Processing: Photolithography, Proton Implantation Metallization



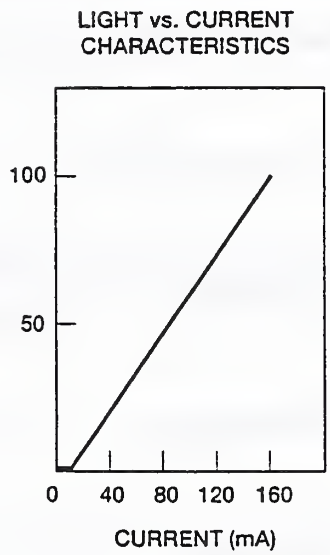
Die Processing: Cleaving and Dicing, Mirror Coating

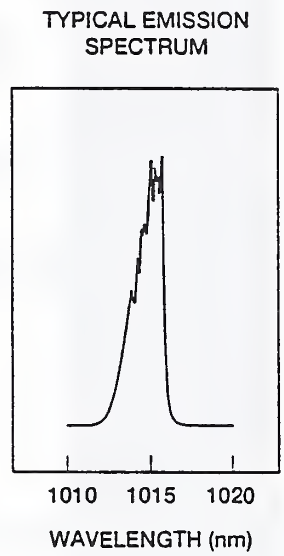


ASSEMBLY
Die Attach,
Wire bonding

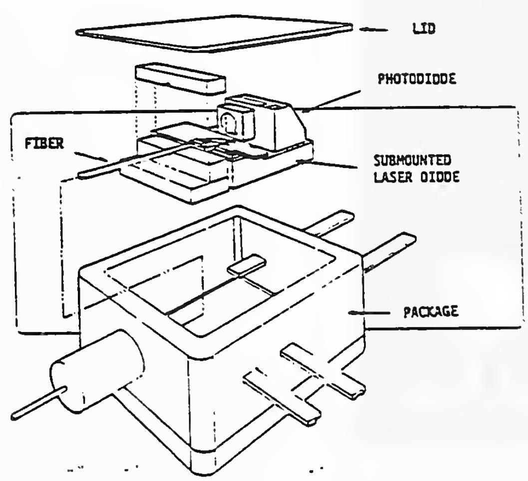


TESTING
Electrical Test,
Optical Test





PACKAGING
Solder Attach,
Fiber Coupling,
Lid Seal



SDL

OPTICAL COMPONENT MANUFACTURING

Operation	*US Industry Competitiveness*	*Relative Mfg Cost*
Epitaxial Growth	*Excellent*	*5%*
Wafer Processing	*Excellent*	*10%*
Assembly	*Average*	*20%*
Packaging	*Poor*	*40%*
Testing	*Very Poor*	*25%*

TECHNOLOGY PROGRAMS

- *Address volume manufacturing needs in the assembly, packaging and test.*

- *Build infrastructure for cost effective manufacturing*

- *Equipment automation in key assembly and test processes*

ADVANCED SILICON OPTICAL BENCH ASSEMBLIES

- *Novel manufacturing architecture: use a common silicon carrier*

- *Combine multiple elements on silicon bench*
  - *laser chips*
  - *photo diodes*
  - *driver circuits*
  - *feedback circuits*
  - *lens*
  - *wave guides*

- *Utilize well developed, automated Si assembly, package technology*

- *Component manufacturers use Novel architecture for product design*

- *Semiconductor equipment manufacturers modify existing equipment to accomodate Si bench*

SDL

FULLY AUTOMATED TESTING

- *Robotics controlled loading*
- *Computer controlled testing*

MANUFACTURING CONTROLLED SOFTWARE

- *Data tracking*
- *Statistical process control*
- *Yield and cost*
- *Test data versus process control parameter correlation*

IMPACT ON KEY INDUSTRIES

FIBER OPTICS COMMUNICATION

- *Telecom, LAN, cable TV*
- *Requires low cost modules ($10 -$20)*

LASER PRINTING

- *Electrographic/thermal printing*
- *Requires low cost lasers*

OPTICAL DATA STORAGE

- *Compact disk, digital video discs, CD-ROM*
- *Requires low cost visible lasers*

SDL

SUMMARY

- *Establish high volume manufacturing of optoelectronic components in the U.S.*
- *Reduce cost structure of such components by a factor of 5 to 20x*
- *Result in a total component market cost savings of greater than $100M*
- *Solidify the U.S. position in optoelectronics based systems; markets that exceed $200B*

ADVANCED TECHNOLOGY PROGRAM

Focused Program

WORKSHOP ON OPTOELECTRONICS AND OPTOMECHANICS MANUFACTURING

U.S. Department of Commerce
NIST
Gaithersburg, Md 20899-0001

White Paper

NOVEL MANUFACTURING TECHNOLOGIES FOR RELIABLE LOW-COST CRITICAL OPTOELECTRONIC DEVICES

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Key words: optoelectronics, manufacturing, automation, fiber optics, communications

This document does not contain proprietary information.

I. PROGRAM GOALS

The goal of this program is to develop new, reliable, and low-cost critical components for wavelength division multiplexing (WDM) communications systems. Unlike other communications technologies, optical technology offers a new dimension - the color of light - to facilitate network functions such as multiplexing, routing, and switching in a transparent fashion. The large-scale deployment of WDM systems for advanced, terabit/sec fiber-optic communications systems will require high-performance, highly-reliable, low-cost components that are not yet available with present manufacturing methods. These high-capacity networks are needed for the full deployment of information superhighways of the future and for the economic benefits that are derived from these systems. New methods of automated, semi-automated, and flexible manufacturing processes are required to meet this goal. Although there are several different possible implementations of WDM technology (*e.g,* multihop networks or single-hop networks such as broadcast and select networks or wavelength routing networks), the components for these different WDM architectures are very similar from a photonics standpoint. The development of low-cost manufacturing methods will have far-reaching implications for many applications in scalable networks that can be applied at the LAN, MAN, or WAN level. The technology would allow the incremental migration from existing networks to new higher capacity networks needed for information superhighways. Moreover, the WDM approach is interoperable with SONET/ATM conventional networks. Incremental migration and interoperabililty are key factors in making an impact on an existing infrastructure which represents hundreds of billions of dollars of capital investment in this country. The development of new automated, semi-automated and flexible manufacturing technologies will provide numerous benefits for WDM system components. These include the following:

- improved component and system reliability
- lower cost by economies of scope
- labor savings in production
- better utilization of production space
- better utilization of capital investment
- reduced need for inventory

- reduced lead times

- reduced work in progress

- rapid programming for different products.

A key business goal of this program would be an order of magnitude reduction in component costs for WDM systems.

II. WDM TECHNOLOGIES

The development of reliable WDM photonic devices will allow a new class of networks that will permit packets of light to pass from sources to destinations in the optical domain at a speed of one terabit/sec - nearly 1000 times greater than conventional hybrid SONET networks available today. Because of the extremely broad optical bandwidth (~ 30 THz) available in the low-loss transmission window of an optical fiber, it is desirable to exploit the fiber bandwidth by wavelength division multiplexing to overcome the electronic limitations and increase the transmission capacity. Early WDM transmission experiments at 10, 16, and 100 wavelength channels with aggregate capacities of 20, 32, and 62 Gb/s, respectively have been reported in 1985, 1988, and 1990.[1] More recently a total capacity of 160 Gb/s through a single mode fiber has been demonstrated in a WDM system with 8 wavelengths at 20 Gb/s for each channel and span-by-span dispersion reversal.[2] In addition, the wavelength or wavelengths can be used as an address to route information without going through electronic add-drop multiplexers which are very expensive at high bit rates. The WDM networks will allow the transmission of high data rate digital and large bandwidth analog signals on different laser wavelengths in an optical fiber. The development and deployment of this technology will require improved manufacturing methods that will provide higher component reliability, lower cost packaging, higher levels of integration, and greater automation for lower cost.

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[1] N.A. Olsson, J. Hegarty, R.A. Logan, L.F. Johnson, K.L. Walker, L.G. Cohn, B.L. Kasper, and J.C. Campbell, Electron. Lett. **21,** 105 (1985); M.P. Vecchi, R.M. Bulley, M.S. Goodman, H. Krobinshi, and C.A. Brackett, Tech. Dig. Opt. Fiber Comm. Conf. paper W02 (1988); C. Lin, H. Kobrinski, A. Frenkel, and C.A. Brackett, Elect. Lett. **24,** 1215 (1988); H. Toba, K. Oda, K Nakanishi, N. Shibata, K. Nosu, N. Takatom and M. Fukuda, J. Lightwave Tech. **8,** 1396 (1990)

[2] A.R. Chraplyvy, A.H. Gnauck, R.W. Tkach, R.M. Derosier, Tech. Dig. Optical Fiber Comm. Conf. paper PD9 (1994)

For reliable WDM communications systems to be cost effective it is important to reduce the component cost per wavelength channel. For example, one approach is to integrate devices with similar functions to form arrays such as laser arrays or photodetector-preamplifier arrays. These arrays can be further integrated with other functions such as wavelength multiplexers and demultiplexers. In spite of its essential role in WDM networks a multiwavelength laser array is not yet available.

A multiwavelength laser array is but one of many possible components that needs to be addressed to build a full WDM system. Specific high-performance and high-reliability components that need flexible, lower cost manufacturing methods include (but are not limited to):

Transmitter modules - low-cost multiwavelength lasers are needed with the associated electronic driving circuitry. Data rates for an individual wavelength should be 1 Gb/sec or greater. The wavelength must be tunable for many applications, although fixed, stable wavelengths can be used in other implementations. Both individual lasers and laser arrays are needed.

Receiver modules - low-cost wavelength tunable receivers are needed for selecting an individual wavelength from the spectrum of wavelengths received. A high level of receiver integration is desired for minimum assembly cost.

Passive wavelength division multiplexers and demultiplexers - large volume, low-cost devices are needed for closely spaced wavelengths. These devices must be able to combine multiple wavelengths onto a single fiber and separate them at the receiver.

Optical isolators and circulators - low-cost, high isolation/directivity isolators and circulators are needed to prevent spurious data, unintended feedback, and other anomalies within a communications system.

Optical amplifiers - low-cost optical amplifiers are needed for boosting the signal level as the signals propagate through a network. This will allow the signals to be regenerated without the need for electronic conversion until the signal reaches its ultimate destination. Optical amplifiers can also be used within optical switches, and as optical preamplifiers for receiver circuits.

Optical switches - optical switches can be used for signal routing, switching, and bridging

between networks. The switch can be used to allow the transmitted WDM data to be routed to one or more of output links. The switch is electronically controlled, and needs to transmit a variety of digital and analog signal formats. Switches need to have protocol transparency, support high data rates, have fast switching speed, and have small excess loss.

Wavelength conversion - devices for directly converting optical signals at one wavelength to another wavelength are needed to maximize network efficiency.

III. INDUSTRIAL CAPABILITIES

Already numerous companies are supporting optoelectronic manufacturing. These companies range from large industrial organizations such as AT&T and other telcos to many smaller businesses such as the author's organization - TACAN Corporation. Critical components have already been experimentally demonstrated, yet large-scale manufacturing has not arrived. For many of these components, the level of integration is much lower than is desired. Already many US-based optoelectronic manufacturers have formed partnerships to promote advances in optoelectronic technology. An ATP-supported, focused effort to foster additional projects would be met with great industry enthusiasm from both manufacturers and end-users.

The telecommunications and cable industries have already embraced optoelectronics for some applications to increase their transmission capacity and broaden their services. However, neither of these industries or any other industry is currently promoting dense WDM technology for near-term deployment. All efforts, so far, have been research activities. As a result, fabrication costs are still high, and very little effort has been placed on manufacturing technologies. The merger of cable, telephony, and data networks will demand new manufacturing technologies, as described here, for reliable, low-cost devices or there will be major bottlenecks to the deployment of information superhighways. Without this, component costs will be so high that the growth of information superhighways will be stifled.

Advances in computers, robotics, machine vision, and other technologies allow for the development of intelligent optoelectronic pick-and-place machines. Such manufacturing breakthroughs with flexible software would allow the fabrication and testing of a variety of different optoelectronic modules for many different applications. In contrast to electronic pick-and-place machines, an optoelectronic device would provide mechanical and optical alignment of various components. In general, a high level of package integration is desired

for major component modules and subsystems; however, there is often a need to integrate dissimilar materials. Ongoing industrial efforts in areas such as epitaxial liftoff and grafting, and optoelectronic micro-assembly on optomechanically patterned substrates have already been developed and are now ready for focused applications to specific programs such as WDM technology.

IV. ECONOMIC BENEFIT

The development of this technology will allow the development of applications such as high resolution image data bases for remote medicine and land management, and fine-grained meta supercomputing for advanced decision support in disaster mitigation. For example, central problems of making medical images are database size, speed of access, and the lack of remote terminal connections. Hospitals and large clinics have very large collections of X-ray, MR, and other images that cannot be discarded and that often need to be accessed rapidly. Often, in a life threatening emergency, several radiologists and other physicians need to look at a sequence of images in color or in fine gray scale to decide a patient's therapy. The deployment of WDM technology would give remote specialists rapid access to high resolution digital images.

In other areas, multimedia conferencing (voice, video, and data) can be implement by WDM approaches. Full motion, high resolution video alone can require 100 Mb/s per person. Thus, only one multiparty multimedia teleconference can rapidly absorb large amounts of network bandwidth. As networks expand (the Internet currently has an estimated 20 million users, and is growing rapidly) the network capacity must be sufficient to allow numerous multimedia conferences.

Optical interconnects are an important component for any data transmission at rates exceeding 100 Mb/s. The reduction in the cost of optoelectronic components for WDM and other applications will have an important impact on a variety of markets such as high-speed LANs and WANs, computer interconnects, switching, and routing matrices, and video-on-demand. Low-cost modules will also impact numerous market sectors for many applications. For example:

	Sector	Applications
1)	Consumer sector	video and multimedia

2)	Military	fiber-optic communications, global grid fiber-optic LANs for mobile platforms (satellites, aircraft, ships, tanks, etc.), fiber gyros
3)	Industrial	factory LANs, machine vision, optical testing, metrology, sensors
4)	Computers	multiprocessor interconnects
5)	Communications	telco, cable TV, private networks LANs, MANs, WANs
6)	Health/medicine	telemedicine, medical information imaging, storage, and retrieval

V. ATP FUNDS

The development and deployment of reliable, cost-effective dense WDM technology will be greatly enhanced by focused ATP funding. The full deployment of these types of systems is currently restricted largely by manufacturing costs and reliability. The cost cannot be reduced until adequate investment is made in automation to reduce the individual costs of components. Investors have been reluctant to invest in individual component developments because advances are needed in manufacturing technology for several different components before the volume will be sufficient to reap the economies of scale. Currently, no single industrial organization has the technology for all of the different components essential for WDM deployment. Thus, industry-wide funding, focused on WDM component manufacturing technology, is desired. For example, the lowest cost laser that is currently commercially available is the compact disc laser. The price here is a reflection of the very large annual production of these lasers for CD audio and CD ROM devices. ATP programmatic funding will allow advances in low-cost manufacturing for many different highly-reliable components, produced by numerous different businesses, needed for the deployment of this technology. Once a threshold is reached, further increases in volume will allow additional cost reduction.

TACAN CORPORATION

ATP WORKSHOP ON OPTOELECTRONICS AND OPTOMECHANICS MANUFACTURING:

NOVEL MANUFACTURING TECHNOLOGIES FOR RELIABLE LOW-COST CRITICAL OPTOELECTRONIC DEVICES

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Tel: (619)438-1010
Fax: (619)438-2412
E-mail: jbechtel@cts.com

February 15, 1995

TACAN CORPORATION

NEED NEW TECHNOLOGY TO MANUFACTURE OPTOELECTRONIC PRODUCTS:

- LESS LABOR
- ADAPTABLE TO MULTIPLE PRODUCTS
- LOW COST
- RELIABLE ASSEMBLY
- AUTOMATED TESTING

TACAN CORPORATION

NEW OPTOELECTRONIC MANUFACTURING TECHNOLOGIES FOR FACTORIES WITH A FUTURE

- NEED TO ASSEMBLE OPTOELECTRONIC MATERIALS AND/OR DEVICES INTO VARIOUS MODULES

- WANT ECONOMIES OF <u>SCOPE</u>

TACAN CORPORATION

NEED NEW TECHNOLOGY TO MANUFACTURE OPTOELECTRONIC PRODUCTS

ADVANTAGES:

- IMPROVED COMPONENT AND SYSTEM RELIABILITY
- LOWER COST
- LABOR SAVINGS IN PRODUCTION
- BETTER UTILIZATION OF PRODUCTION SPACE
- BETTER UTILIZATION OF CAPITAL INVESTMENT
- REDUCED LEAD TIME
- REDUCED INVENTORY
- REDUCED WORK IN PROGRESS
- RAPID PROGRAMMING FOR DIFFERENT PRODUCTS

TACAN CORPORATION

PROGRAM GOALS:

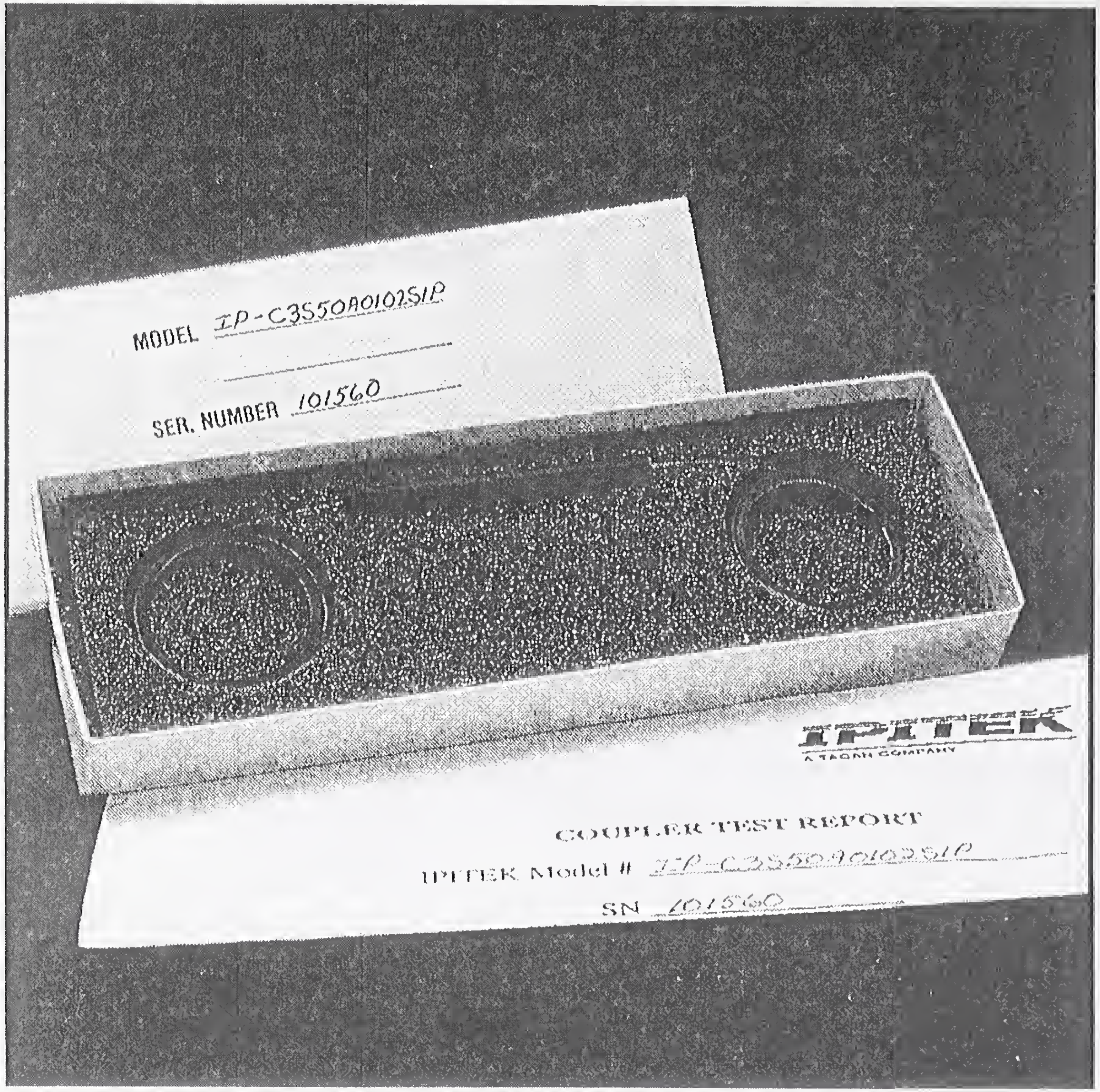
DEVELOP NEW, RELIABLE LOW-COST CRITICAL COMPONENTS FOR WAVE-LENGTH DIVISION MULTIPLEXING COMMUNICATIONS SYSTEMS.

TACAN CORPORATION

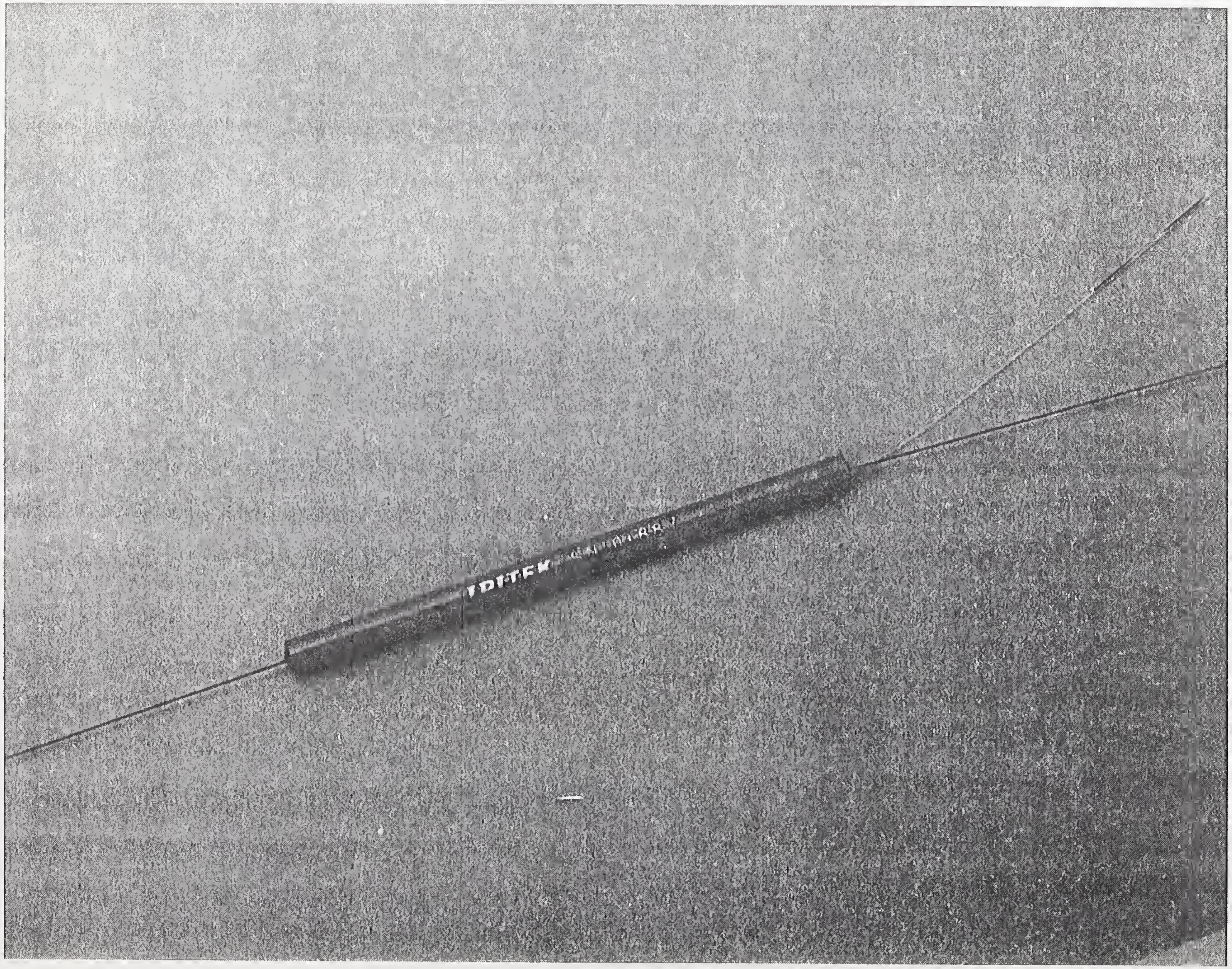
WDM TECHNOLOGIES

MODULES

- MULTIWAVELENGTH LASER TRANSMITTERS
- TUNABLE OPTICAL RECEIVERS
- PASSIVE WDM COUPLERS
- OPTICAL ISOLATORS AND CIRCULATORS
- OPTICAL AMPLIFIERS
- OPTICAL SWITCHES
- WAVELENGTH CONVERSION


MODEL IP-C3550A0102SIP
SER. NUMBER 101560
IPITEK
A TACAN COMPANY
COUPLER TEST REPORT
IPITEK Model #
SN 101560

TIACAN
CORPORATION



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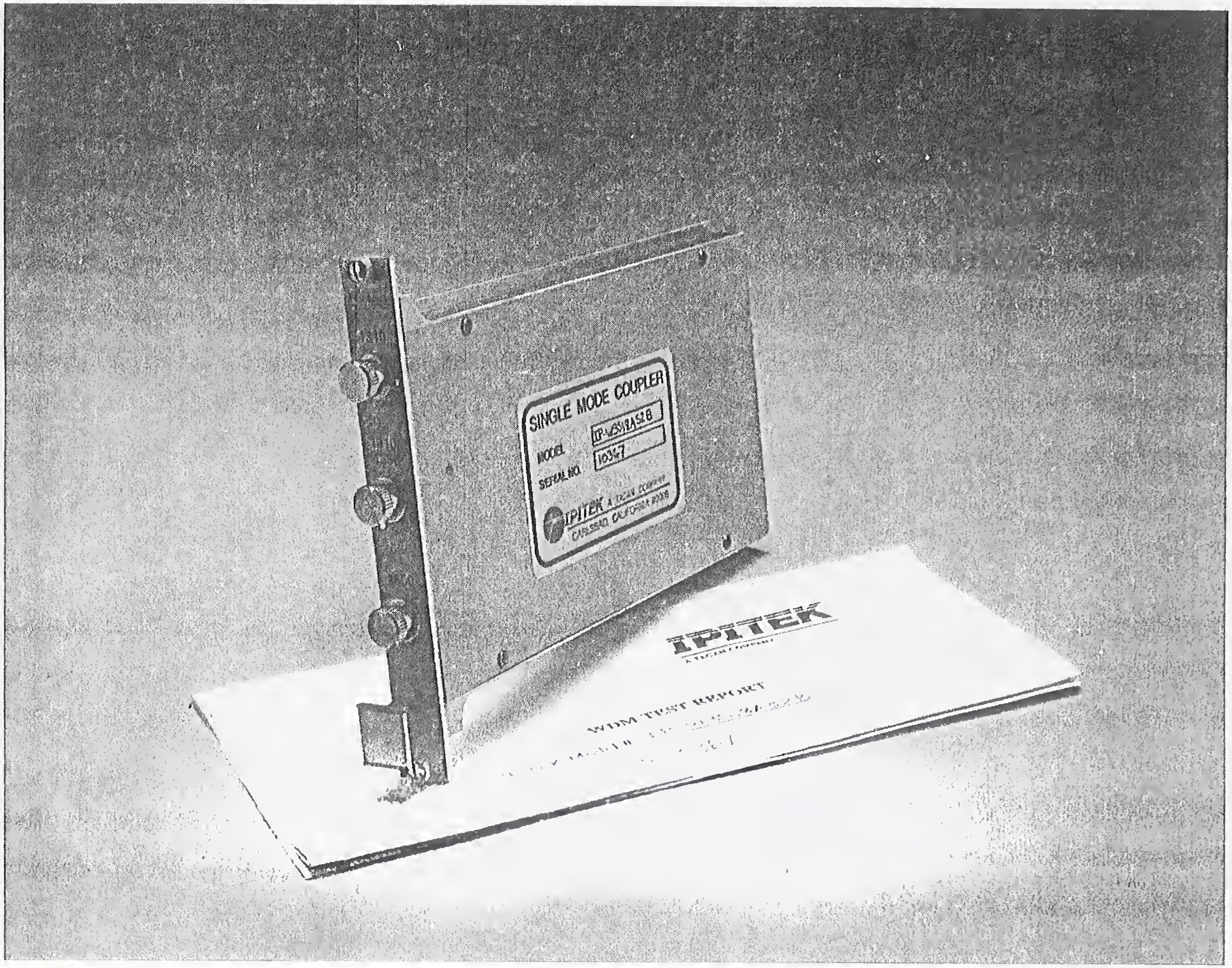

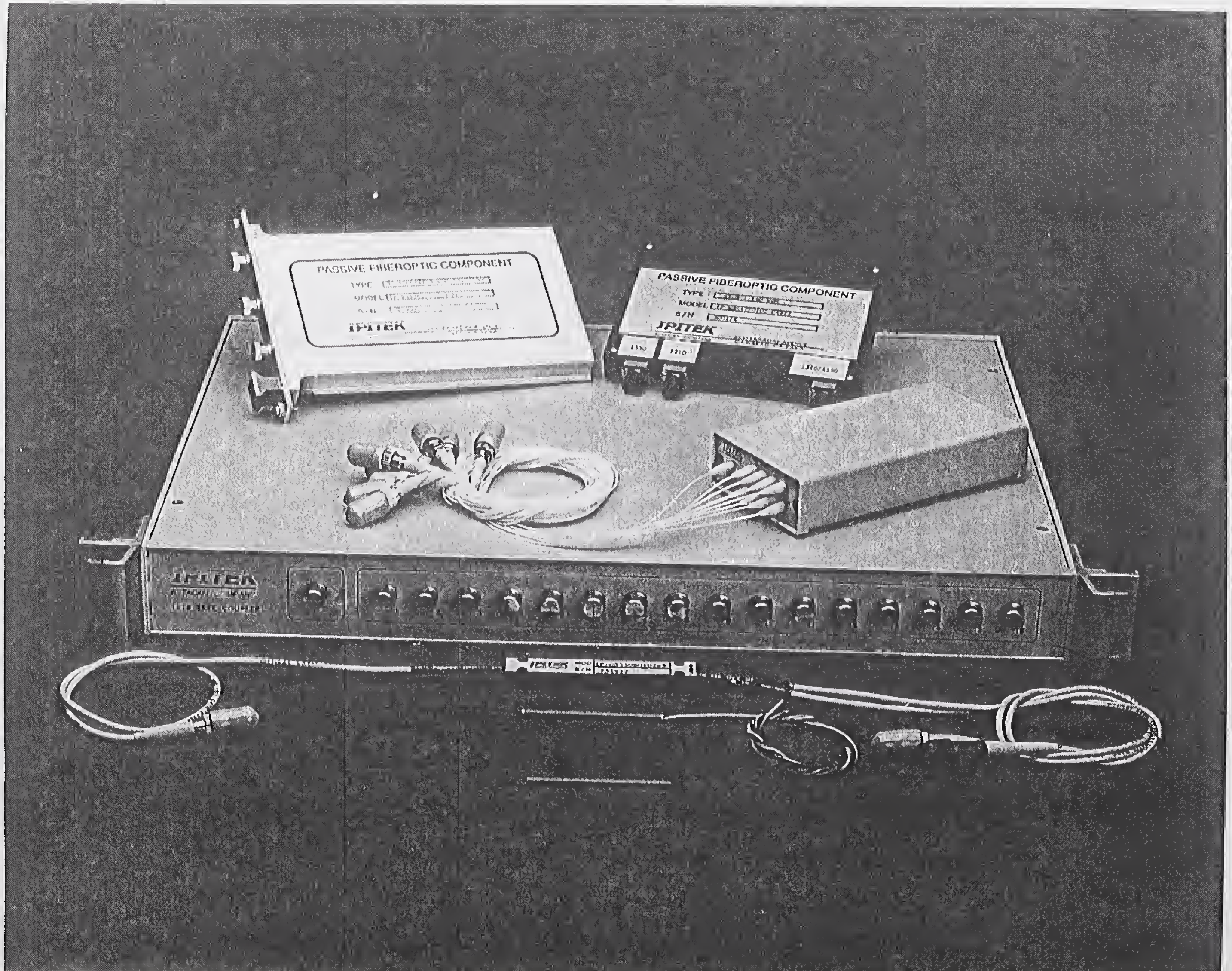
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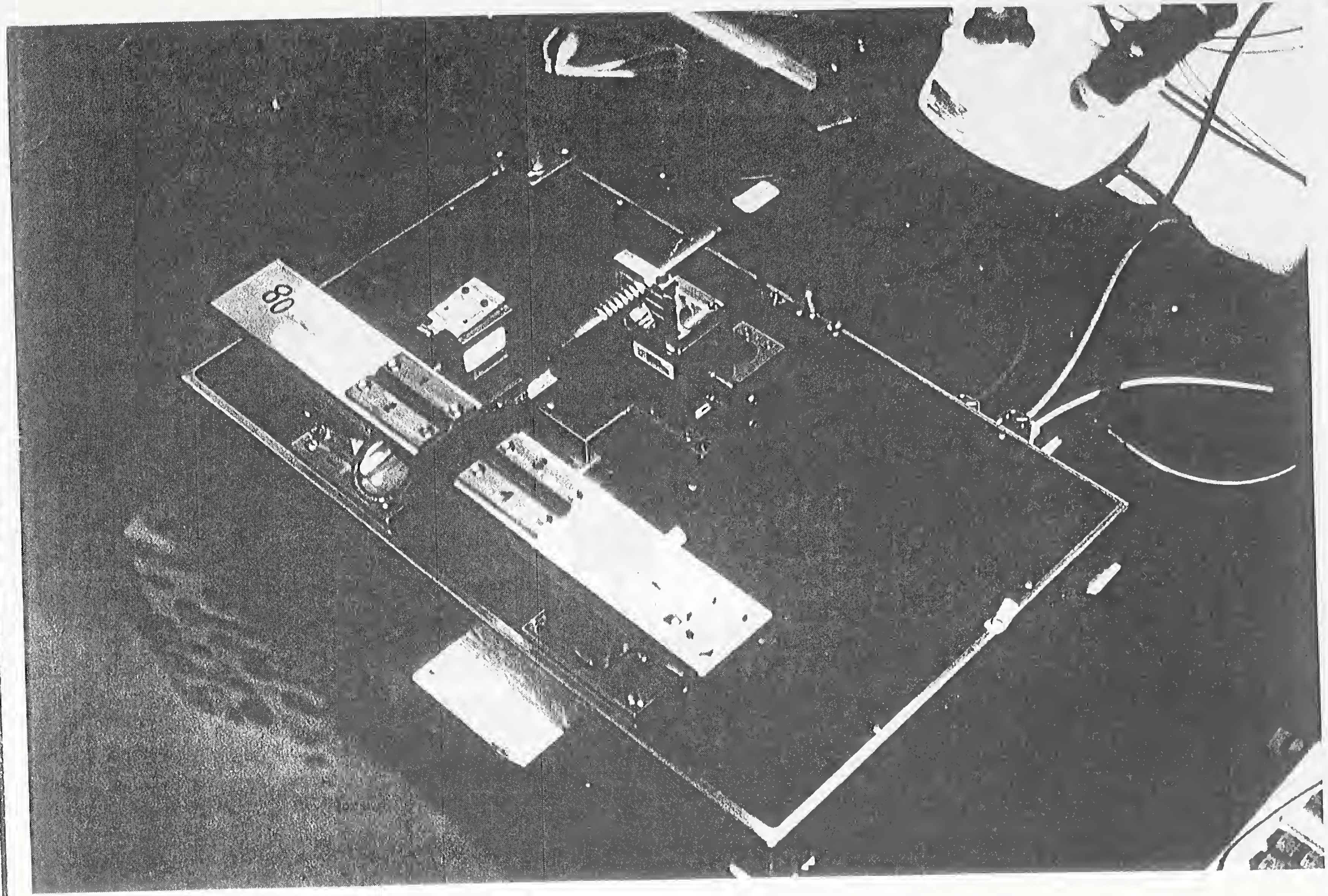
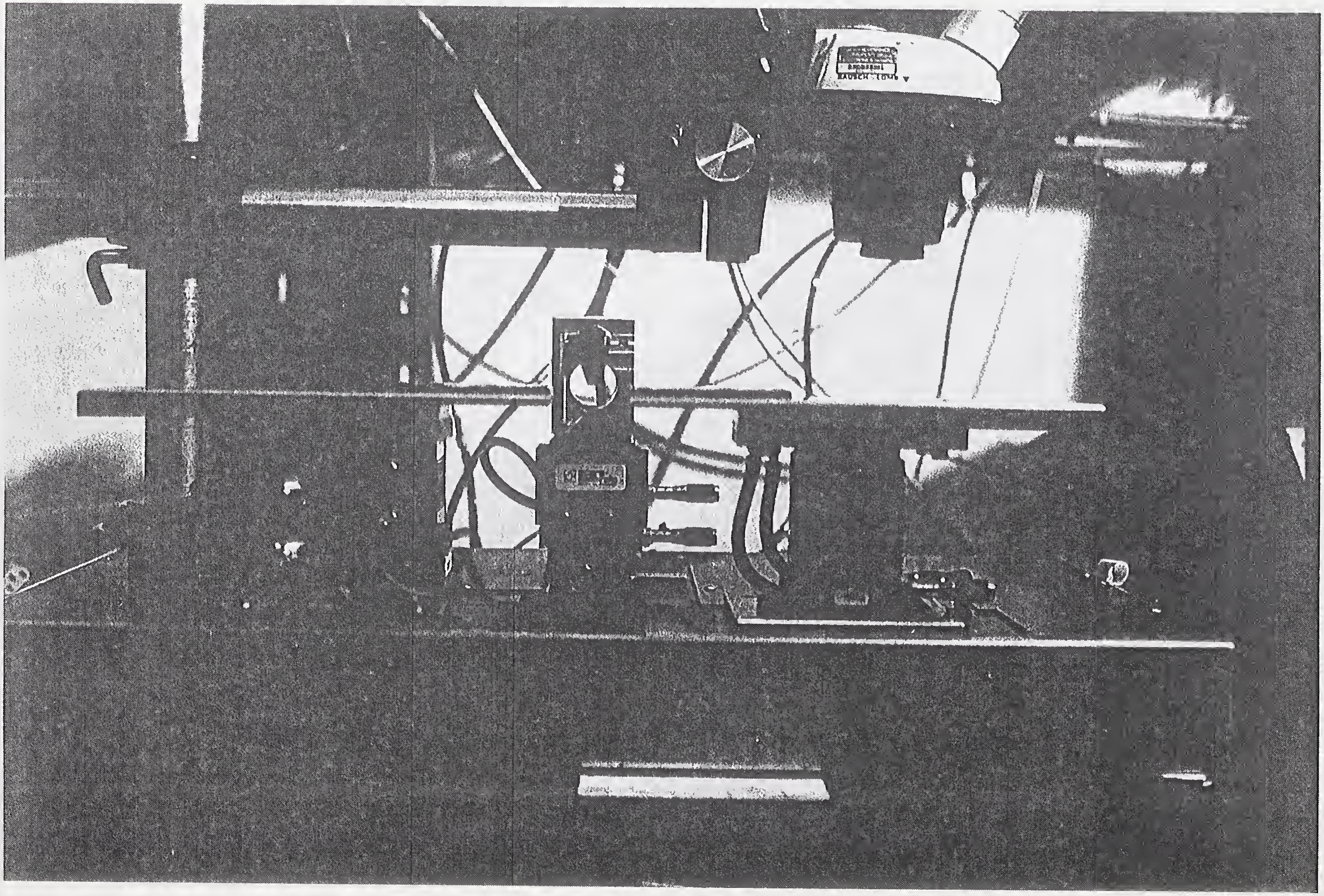
IACAN
CORPORATION



TACAN
CORPORATION



TACAN CORPORATION

NEW OPTOELECTRONIC MANUFACTURING TECHNOLOGIES:

EXAMPLE:

INTELLIGENT FIBER-OPTIC COUPLER MANUFACTURING

- ROBOTIC FABRICATION
  (Automated Fiber Stripping, Cleaning, Fusing, Packaging)
- COMPUTER CONTROLLED (Micro Computers)
- NEURAL NETWORKS USED TO IMPROVE YIELDS IN FIBER FUSION
- AUTOMATED COUPLER TESTING
- FLEXIBLE SOFTWARE
- CAN BE USED FOR A WIDE VARIETY OF FIBER-OPTIC SPLITTERS, COMBINERS, (Singlemode, Multimode, and Polarization Maintaining) AND WAVELENGTH DIVISION MULTIPLEXERS.

TACAN CORPORATION

NEW OPTOELECTRONIC MANUFACTURING TECHNOLOGIES:

EXAMPLE:

INTELLIGENT OPTOELECTRONIC PICK AND PLACE SYSTEMS

- COMPUTER CONTROLLED
- ROBOTICS TO MOUNT INDIVIDUAL OPTOELECTRONIC COMPONENTS
- MACHINE VISION
- NEURAL NETWORKS FOR PATTERN RECOGNITION TO FACILITATE OPTICAL ALIGNMENTS
- SOFTWARE FLEXIBILITY TO ADAPT TO FABRICATION OF A VARIETY OF DIFFERENT MODULES

TACAN CORPORATION

INDUSTRIAL CAPABILITIES

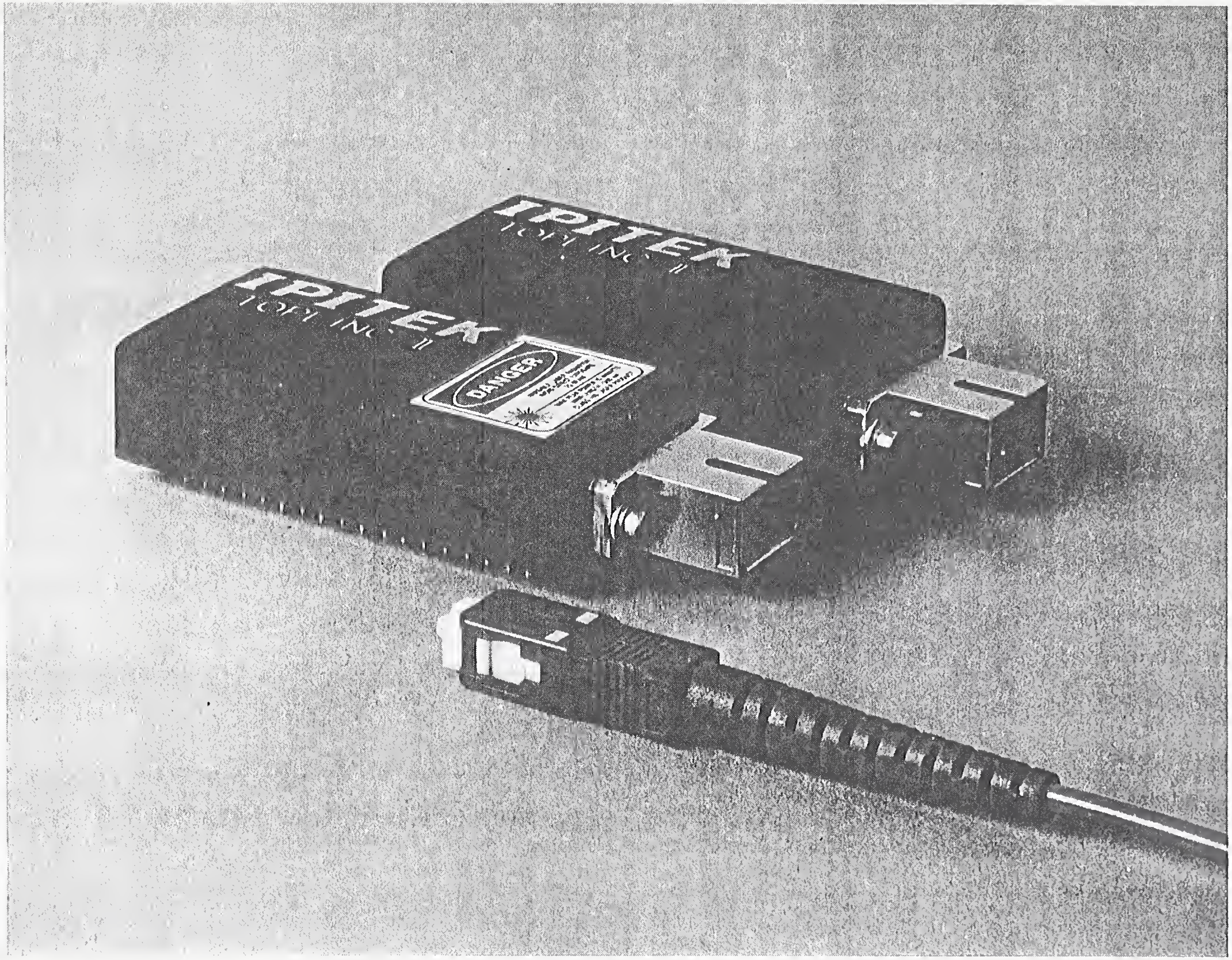
- MANY U.S. CORPORATIONS ALREADY IN OPTOELECTRONICS MANUFACTURING
- NO SINGLE LEADER, MANY SMALL COMPANIES
- ASSOCIATED ADVANCES IN
  - COMPUTERS
  - ROBOTICS
  - SOFTWARE/NEURAL NETWORKS
  - MACHINE VISION
- INDUSTRIAL EFFORTS IN ADVANCED PACKAGING

  e.g., microassembly
  epitaxial grafting
  lithography

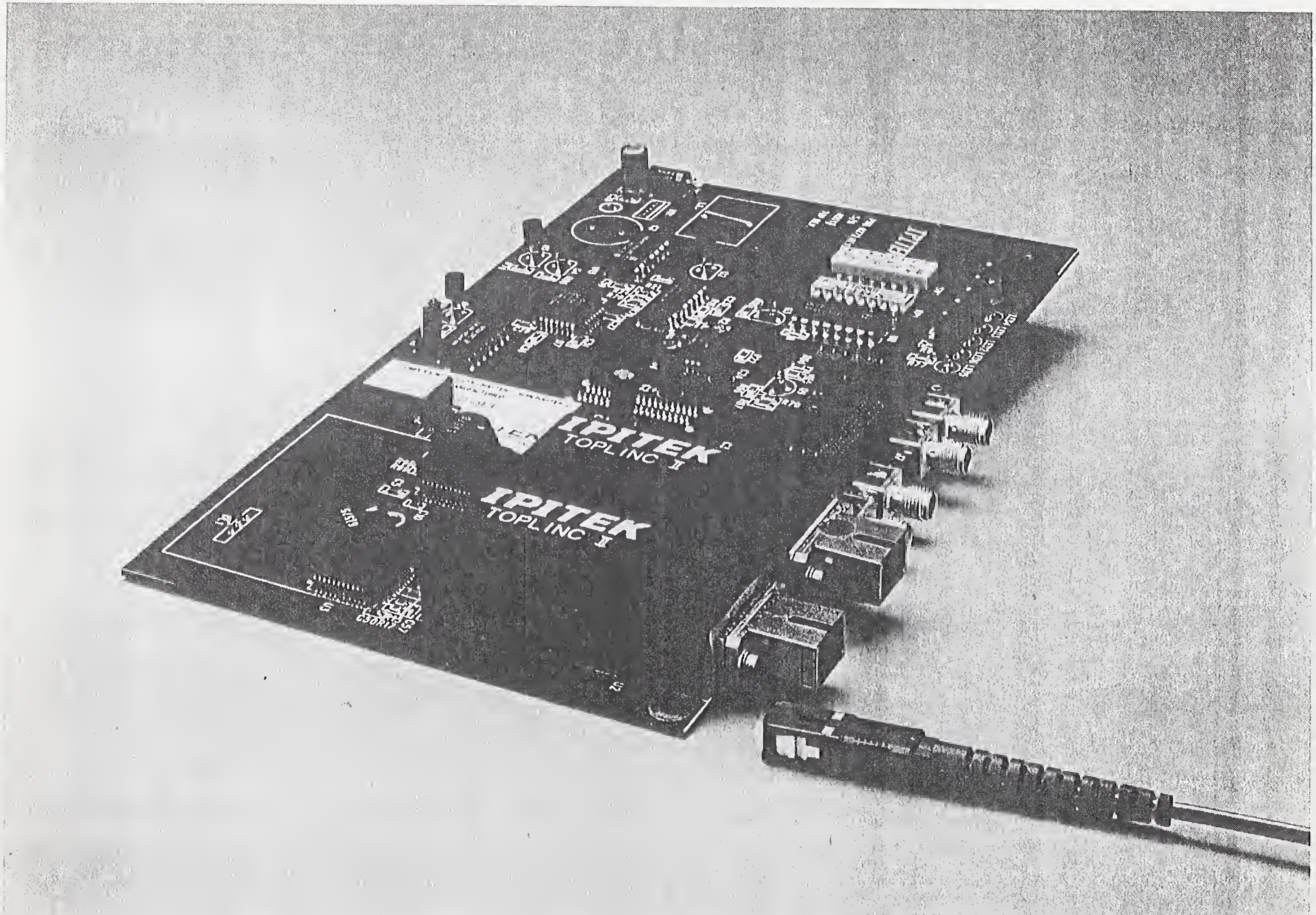
TIACAN CORPORATION

LOW-COST TOPLINC II

- 1.25 GBIT TRANSMITTER & RECEIVER
- LOW COST SHORT WAVELENGTH LASER & SILICON DETECTOR
- SINGLE SUPPLY, LOW POWER CONSUMPTION
- REDUNDANT OPEN FIBER CONTROL ALARMS
- 1 KILOMETER MULTIMODE OPERATION
- FIBER CHANNEL FCO COMPATIBILITY


IPITEK
IPITEK
DANGER

TIACAN
CORPORATION



TACAN CORPORATION

ECONOMIC BENEFIT:

WDM SYSTEMS

SECTOR	APPLICATION
CONSUMER	VIDEO, MULTIMEDIA
MILITARY	FIBER-OPTIC COMMUNICATOR GLOBAL GRID LANS FOR MOBILE PLATFORMS FIBER GYROS
COMPUTERS	MULTIPROCESSOR INTERCONNECTS
INDUSTRIAL	FACTORY LANS, SENSORS MACHINE VERSION
COMMUNICATIONS	TELCO, CABLE TV, PRIVATE NETWORKS, LANS, MANS, WANS
HEALTH/MEDICINE	TELEMEDICINE, MEDICAL INFORMATION IMAGING, STORAGE, RETRIEVAL

TACAN CORPORATION

ATP FUNDING

NEED FOCUSED PROGRAM:

- NO SINGLE MANUFACTURING LEADER
- NEED ADVANCES FOR ALL COMPONENTS
- SMALL INDUSTRIAL COMPONENT MANUFACTURERS OFTEN HAVE INSUFFICIENT RESOURCES FOR FACTORY AUTOMATION

New MEMS Manufacturing Technology for Micro-Optical Data Storage Heads and Fiber-Optical Switches

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The goal of this white paper is to propose a new program idea of manufacturable optical MEMS technology [1] for high-volume, low-cost manufacturing of <u>optical data storage read/write heads</u> and <u>fiber-optical switches</u> products.

The micro-electro-mechanical-system (MEMS) technology already has a great impact in manufacturing new optoelectronic products. For example, the digital micromirror chip is being pursued by Texas Instruments for projection displays. At UCLA, we have developed another manufacturable optical MEMS technology that would allow free-space optical systems be monolithically integrated on a single chip (Fig. 1). The "micro-hinge" technology developed by Pister *et al* [2] allows optical elements be fabricated by planar IC-like process and then "folded" into three-dimensional structures. An example of three-dimensional micro-Fresnel lens [3] is shown in Fig. 2. Mirrors, beam-splitters, translational stages, and rotary stages can all be constructed in similar processes [1].

We propose to apply this technology to mass-market products such as <u>single-chip read/write heads for optical data storage</u>, and <u>low-cost fiber-optic switches for FDDI and other fiber networks</u>. By integrating lenses, beam-splitters, photodetectors, signal processing circuits all on a single chip, the expensive assembly cost of the optical read/write heads (Fig. 3) will be eliminated. The optics is pre-aligned in the CAD layout stage. Furthermore, the single chip optical head also enhances the performance (capacity and data transfer rates) of optical data storage systems thanks to the reduced mass and size of the heads. Many fiber optic products also benefits from this technology. Figure 4 shows the schematic diagram of a tunable Fabry-Perot filter for wavelength-division-multiplexed (WDM) optical fiber networks. This design permits large volume and low-cost manufacturing. Optical bypass switch for FDDI networks can also be constructed similarly. <u>A cost reduction of 100 times and volume reduction of 1000 times are expected.</u>

The impact of this new technology on US optoelectronic industries is enormous. Successful development of this technology will give US optoelectronic industries a quantum leap in the manufacturing of micro-optical systems, and help US re-gain the market share of the increasing worldwide optoelectronic markets.

<u>Reference:</u>

1. M. C. Wu, L. Y. Lin, and S. S. Lee, "Micromachined Free-Space Integrated Optics," Proc. SPIE, Vol. 2291, *Integrated Optics and Microstructures II*, San Diego, California, July 28, 1994 (Invited Paper).
2. K. S. J. Pister, M. W. Judy, S. R. Burgett, and R. S. Fearing, "Microfabricated hinges," *Sensors and Actuators* A, Vol. 33, pp. 249-256, 1992.
3. Y. Lin, S. S. Lee, K. S. J. Pister, and M. C. Wu, "Micro-machined three-dimensional micro- optics for integrated free-space optical systems," *IEEE Photonics Technol. Lett.*, Vol. 6, p. 1445, 1994.

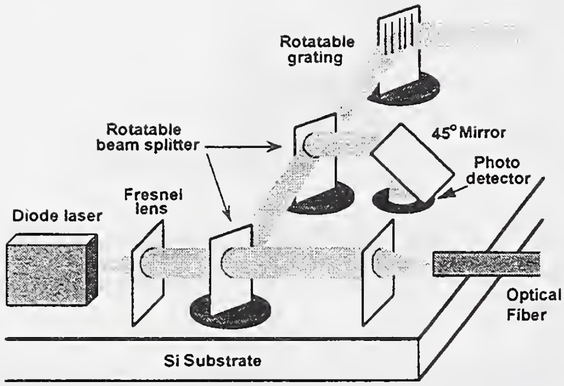


Fig. 1. Free-space micro-optical system using micro-hinges and manufacturable MEMS technology.

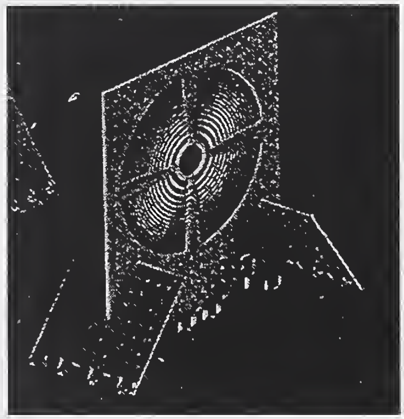


Fig. 2. Three-dimensional micro-Fresnel lens.

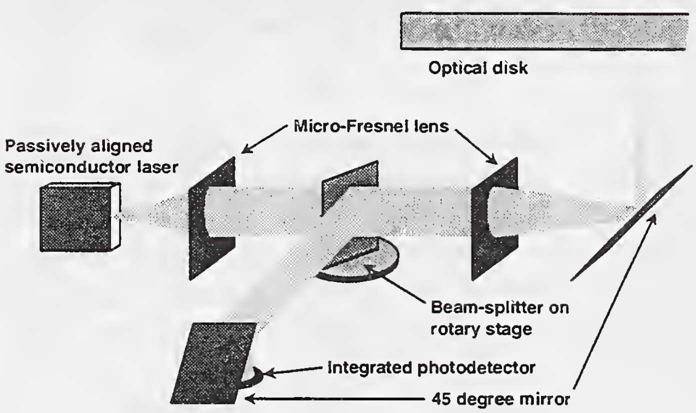


Fig. 3. Schematic of the fully integrated single-chip optical data storage read/write head.

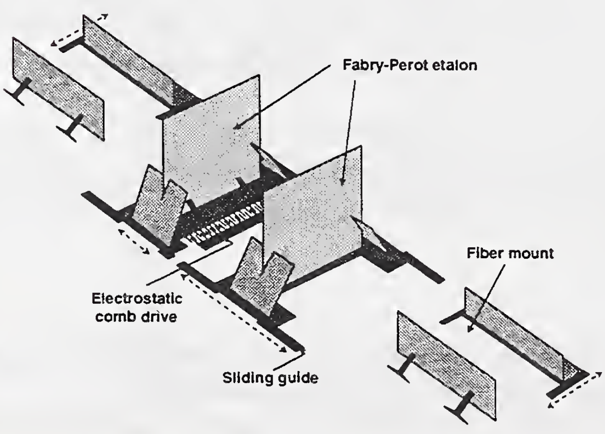


Fig. 4. Low-cost fiber-optic components made by manufacturable MEMS technology.

NIST Workshop on:

Optoelectronic Manufacturing

Gaithersburg, MD
2/15/95

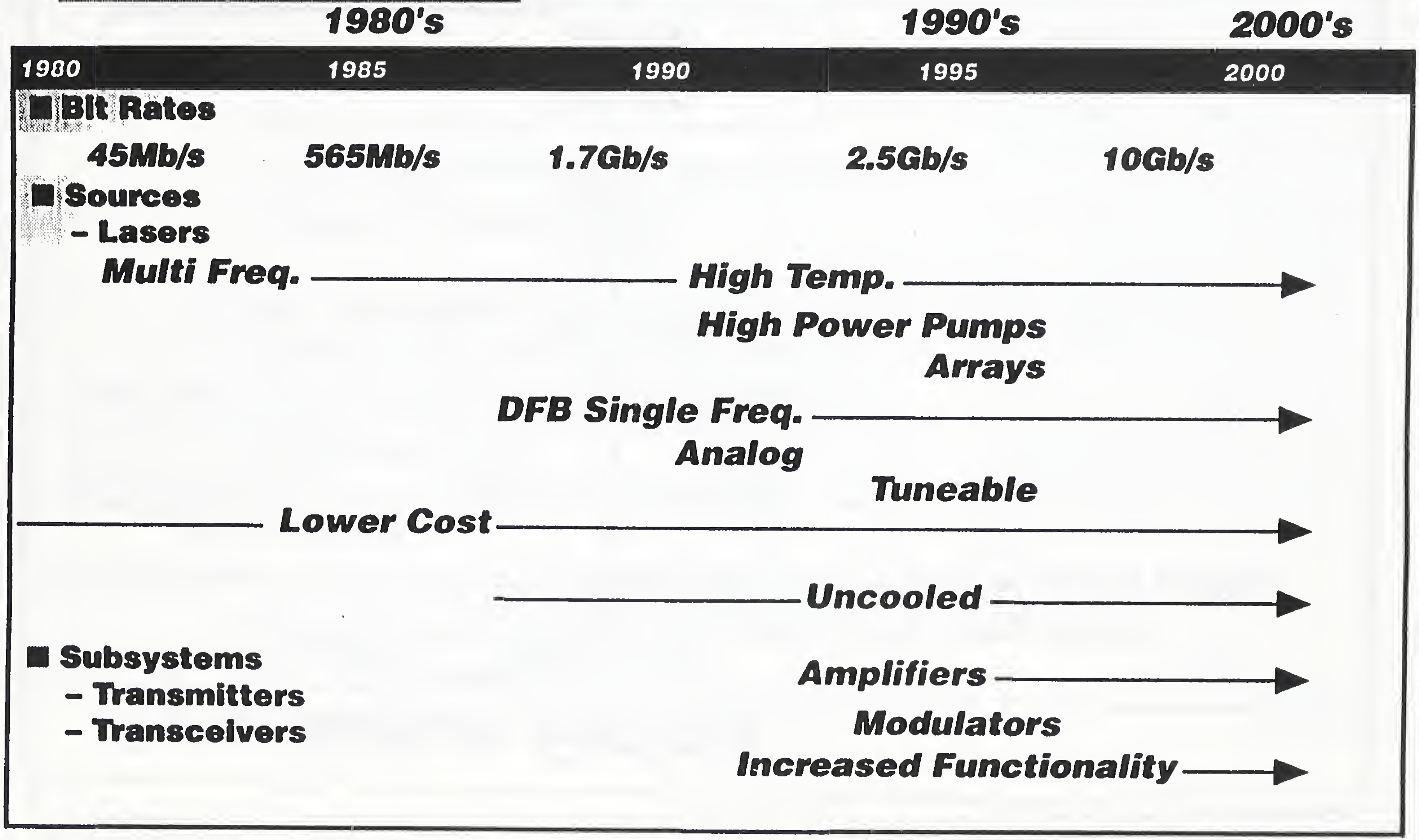
Thomas Stakelon
AT&T Optoelectronics
Breinigsville, PA
Phone 610 391-2741
Fax 610 391-2668

Optoelectronics Manufacturing Outline

1. Technology evolution
2. Opto-module factory schematic
3. Application examples
4. Production cost
5. Breakthroughs
6. Manufacturing process roadmap
   - Other key processes

AT&T

Lightwave Technology Evolution



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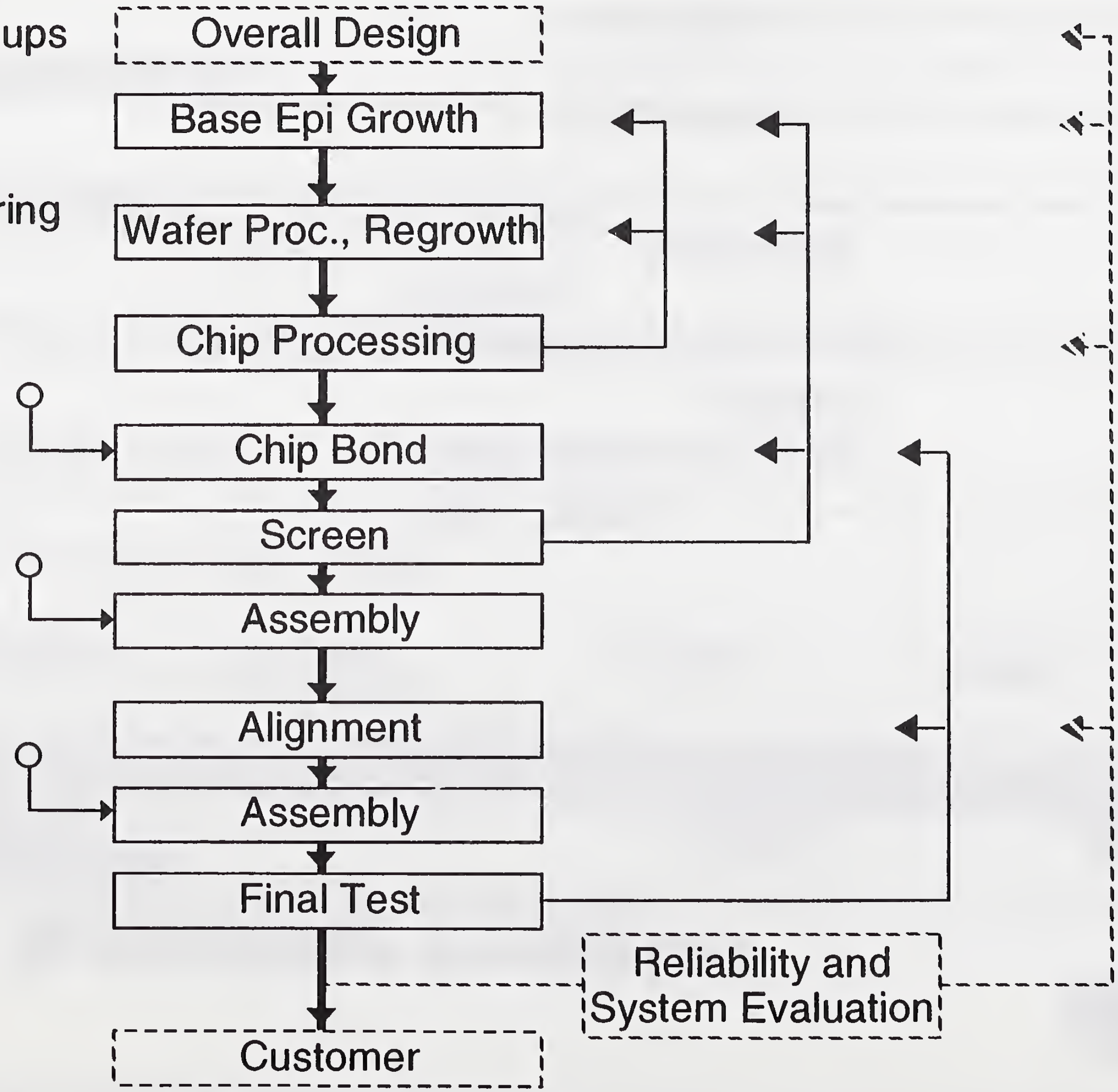
Opto-Module Factory

- Major operation groups
- Product flow
- Feedback loops during start-up or change
- Parts feed ○



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Application Examples

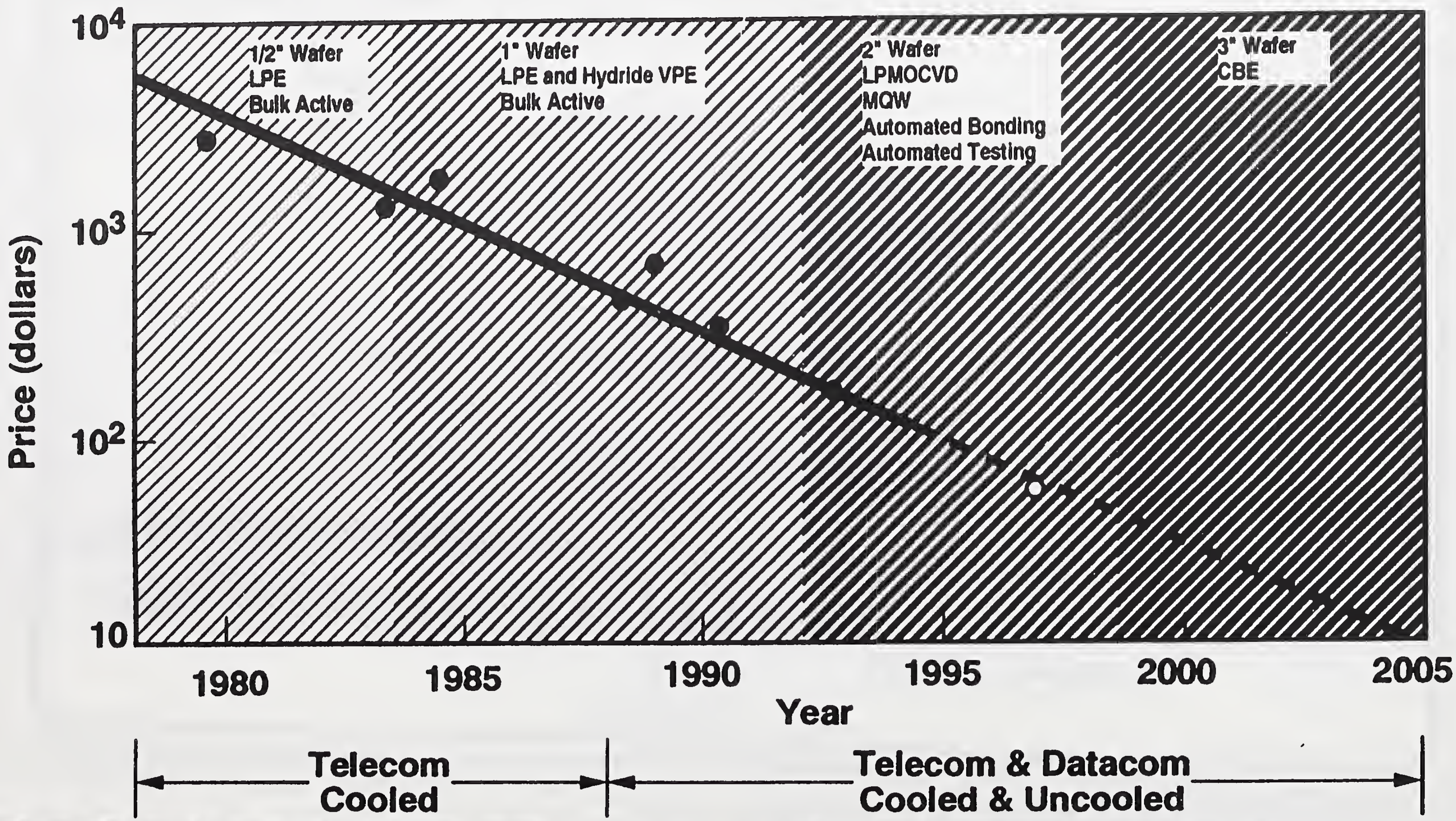
1. Uncooled laser modules for fiber-in-the-loop applications
   - Must be low cost
   - Volumes at 1M/year at end of decade
   - Fabry-Perot laser chips

2. High performance laser modules for trunk digital and CATV
   - Prices >10X uncooled laser module
   - Volumes at 1/10 uncooled laser
   - DFB laser chips

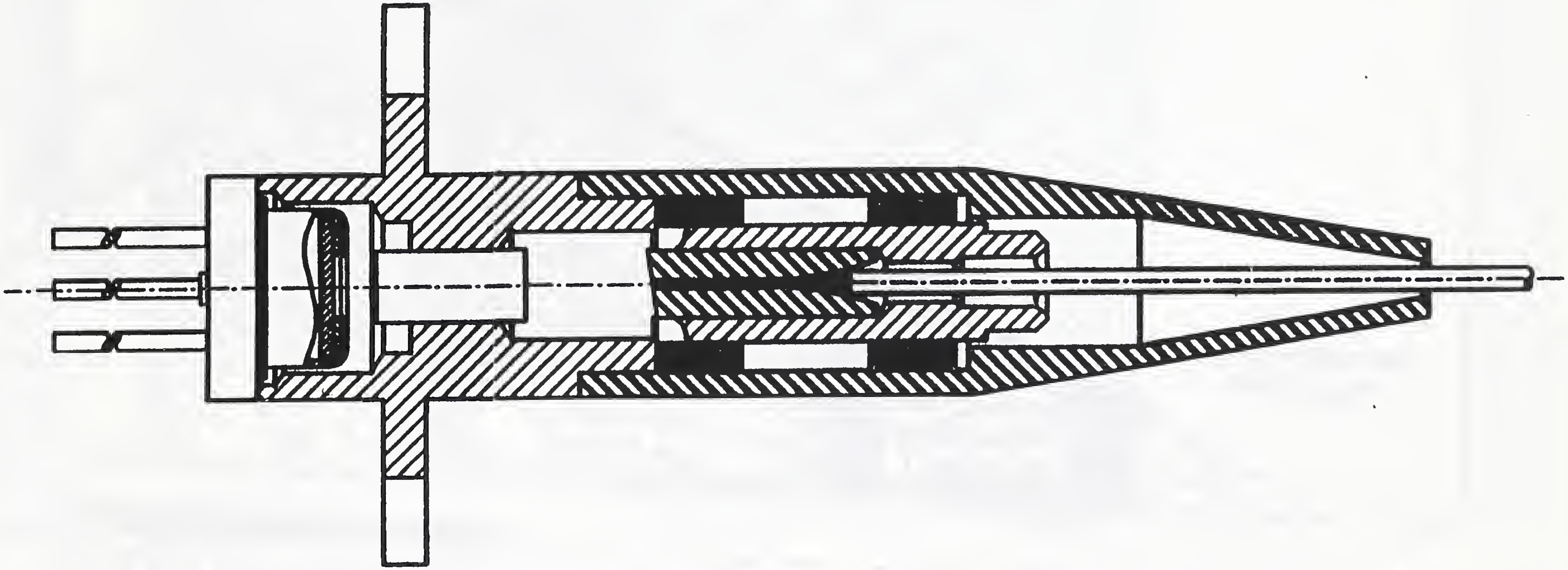
KEY POINTS:

- Commonalities at growth, chip and package level are feasible.
- Breakthroughs needed for sustained competitiveness for both products.
- Expertise and investments needed.

Low Cost Laser Packages for Telecom & Datacom

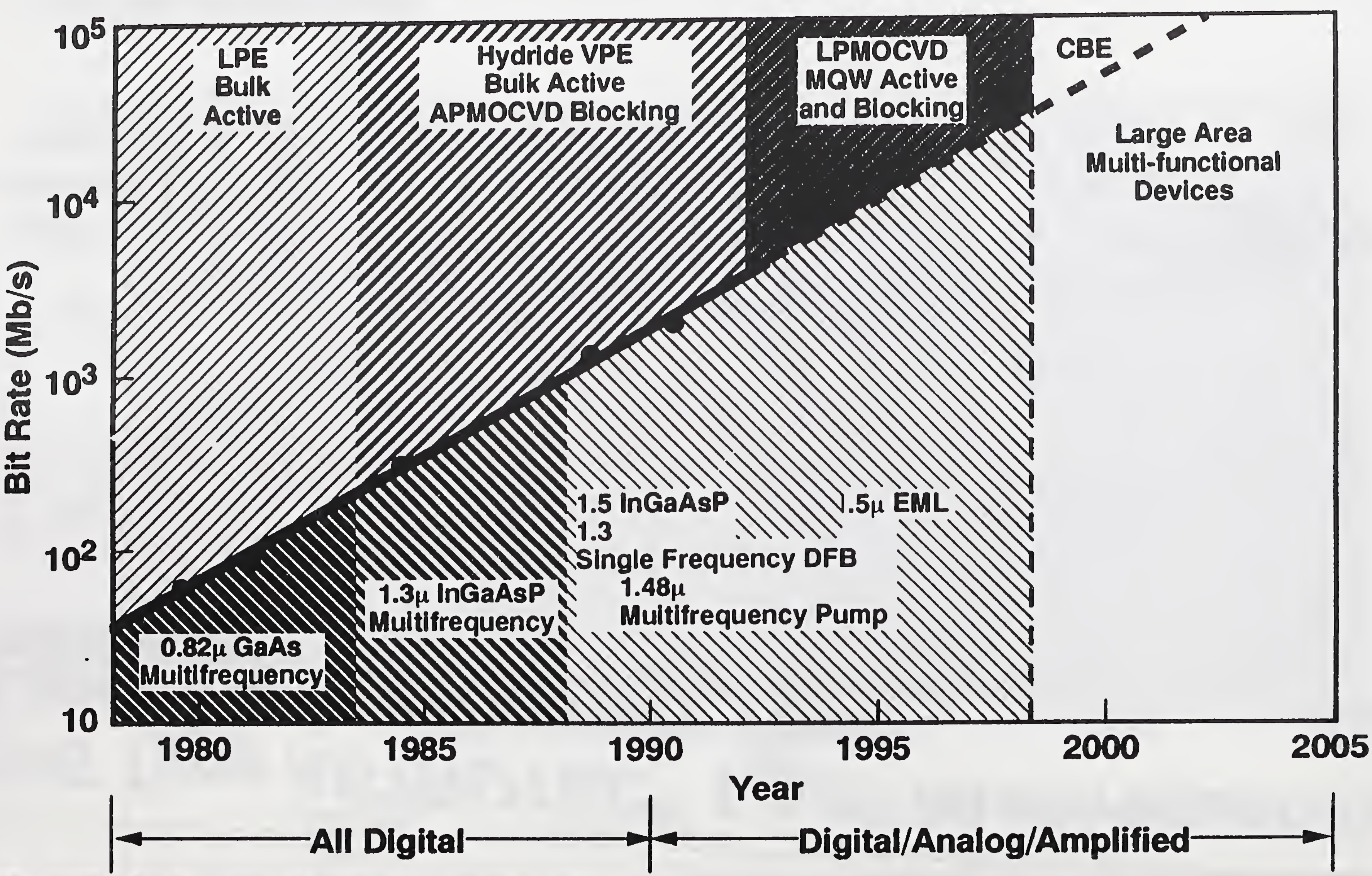


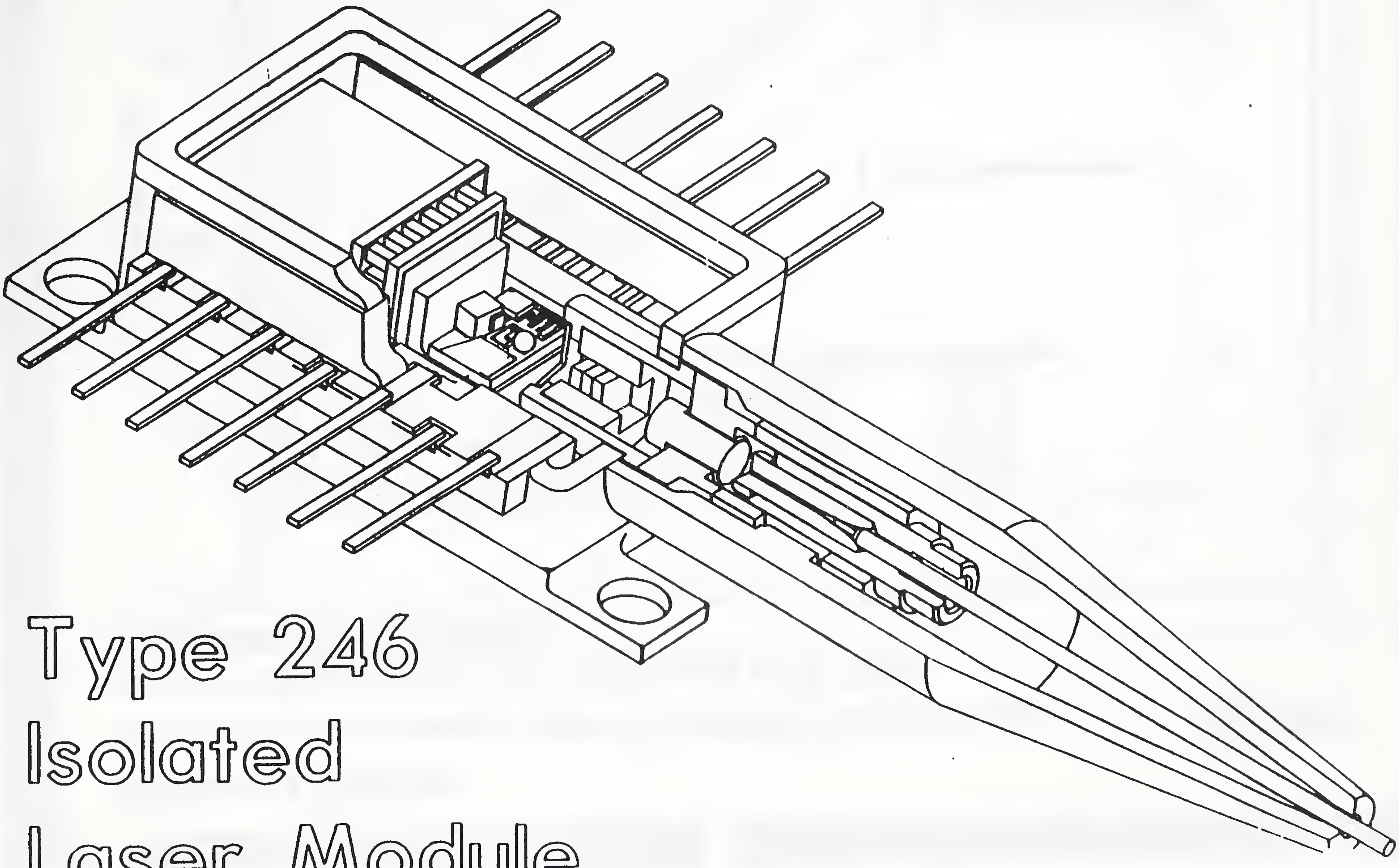
245 Type ASTROTEC® 1.3μm Multifrequency Laser Module Cutaway View



AT&T

High Performance Lasers for Telecom & CATV



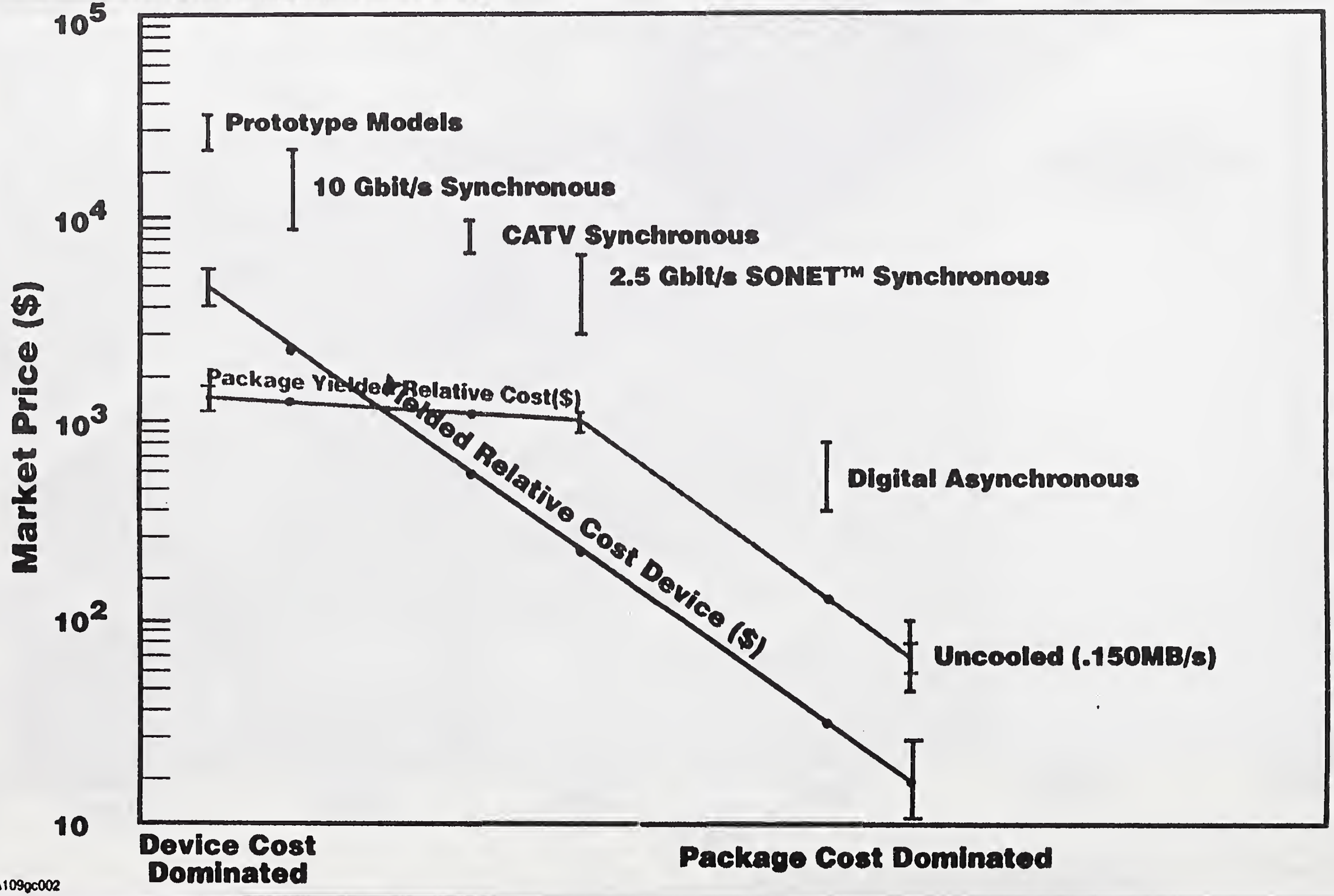


Type 246
Isolated
Laser Module

Market Price

High Performance and Uncooled Low Cost Laser Packages for Telecom (1Q '94)

AT&T



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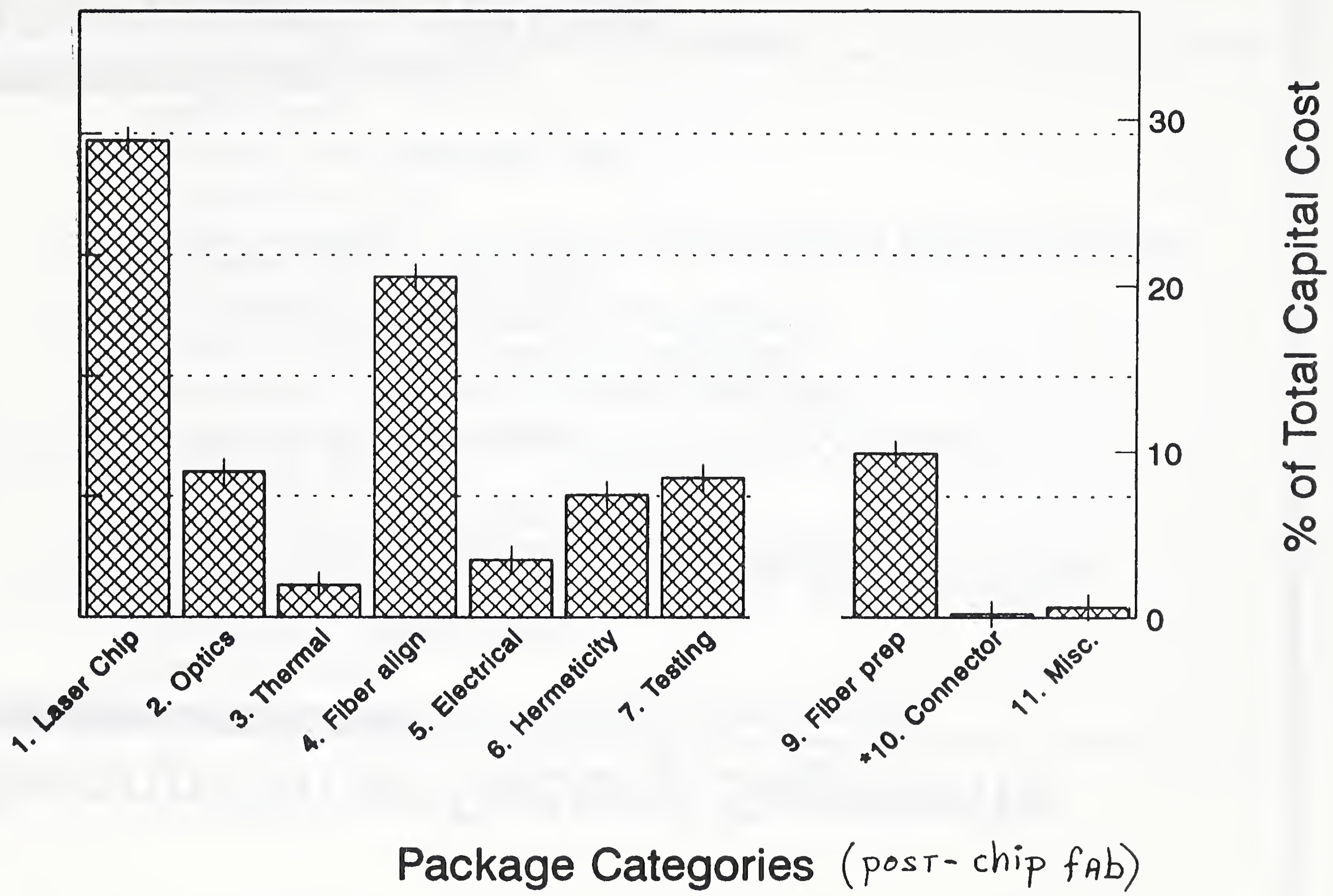

% of Total Capital Cost
0
10
20
30
1. Laser Chip
2. Optics
3. Thermal
4. Fiber align
5. Electrical
6. Hermeticity
7. Testing
9. Fiber prep
*10. Connector
11. Misc.
Package Categories (post-chip fab)

Description of Factory Segments

1. Base Epi growth
   - Uniformity, dopant control
   - Characterization
2. Wafer processing, regrowth, chip processing
   - Uniformity, dopant control
   - Characterization
   - Chip handling automation
3. Pill assembly (chip bond, screen, assembly)
   - Vision control, automation of assembly
   - Moderate bonding precision (±5 micron)
   - Screen, test on submount
   - Yield is critical
   - Hermetic seal (?)
4. Alignment, final assembly, test
   - Many parts
   - Automation desirable
   - Precision fiber alignment (±0.5 micron)
   - Hermetic seal (?)
5. Reliability and system evaluation
   - Performed on final product and Pill assembly

Breakthrough Drivers

- All products are on steep downward price curves (40% to 20% per year)
- Chip yields improve in early part of cycle
- Package cost dominates in later part of cycle
- Volumes are low by silicon standards

Feasible Breakthroughs

- Common laser structures
- Precision chip bonding ($\pm 5 \rightarrow \pm 0.56$ micron)
  - Vision system
  - Self-alignment
- Rapid, flexible chip on submount screen and test equipment
- One "Pill" for both high performance and low cost modules
- Automatable (or Batch) (± 0.5 micron) final alignment for fiber
- Low package material cost:
  - Inexpensive precision parts (e.g. Si)
  - Stable molded plastics
  - Hermeticity
- Reduced testing time

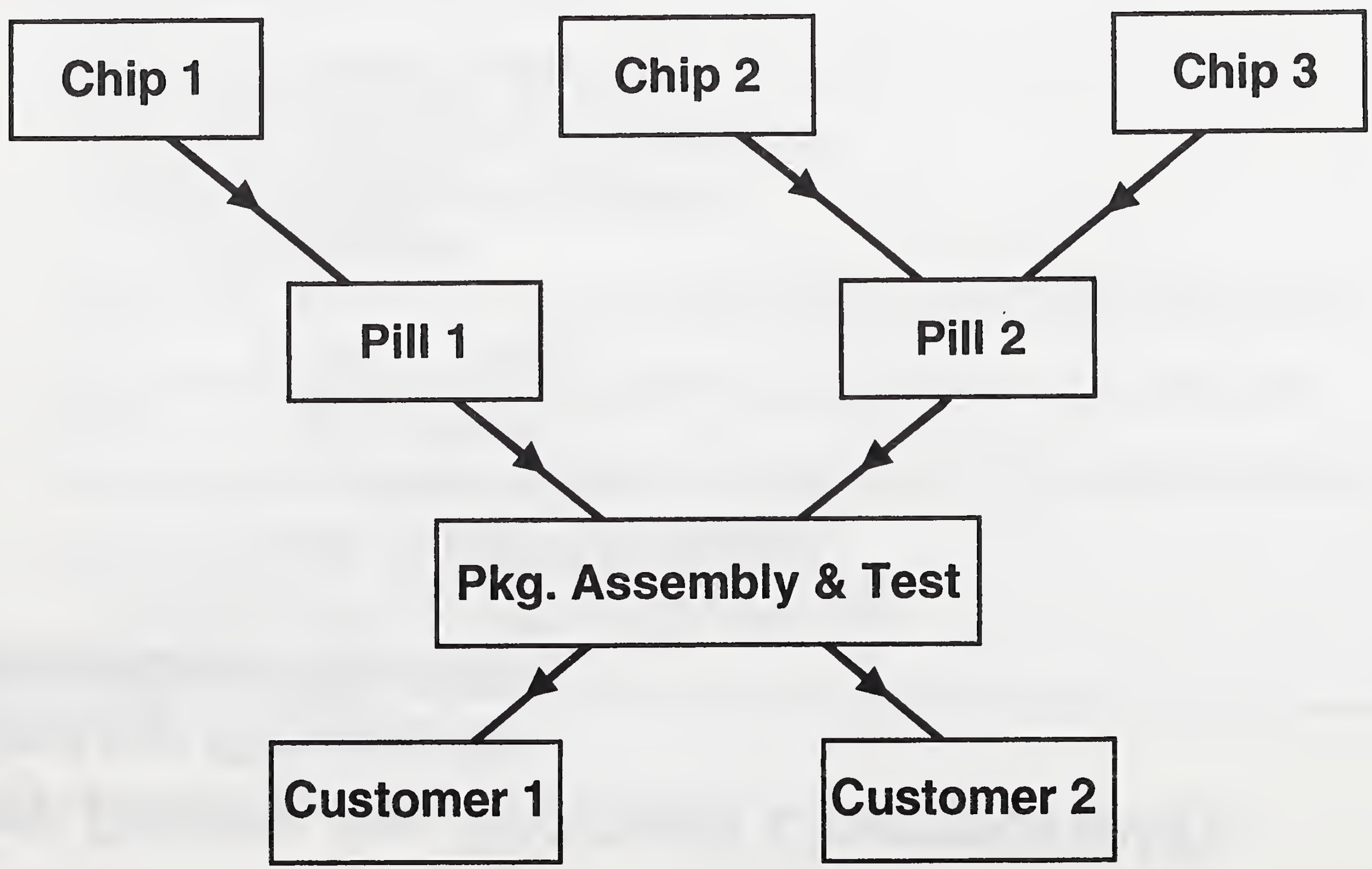
Key Points for Process Commonality Among Products

1. Wafer growth & processing
   - Laser structure
   - Epi method
   - Reactor types

2. Chip level
   - Bonding equipment
   - Screen & test equipment
   - Handling methods

3. Package level
   - Common pill
   - Modular assembly of other parts
   - Final test equipment

Example: Configuring Segments



Criteria for Process or Equipment Developments

Process development must lead to process and/or equipment that meet manufacturing imperatives:

- Transferable to integrated manufacturing operation
- Scalable to market levels
- Meet market cost trends
- Sufficient commonality

Optoelectronic Process Roadmap*

Major Process Groups	Current	3-5 years	Next
Optical Semiconductor Component Packaging	• Low precision chip bonding • Manual handling and assembly • High material cost • Hermetic sealing of lasers • Active optical alignment • Movement during submicron optical assembly	• Fully automated chip bond and test • Automated handling and precision joining of small parts • Low cost materials and precision parts • Submicron optical assembly without movement • Reliable nonhermetic enclosures • Automated handling for packaging, tests	• Automated passive optical alignment of single chips and arrays • Array and OEIC package assembly
Optical Semiconductor Devices (laser diodes unless indicated)	• Wafer certification by chip test • Partial automation of chip handling and testing • Humidity sensitive • Low-med yields • Acceptable LED and detector processes	• Wafer-scale probing • In situ growth process control • Fully automated chip handling and testing • Humidity passivated	• Processes for passive optically aligned structures • Processes for arrays and OEICs • Processes for tunable lasers, filters, modulators
Optoelectronic Subsystem Assembly	• Manual assembly of optical and electronic components • Manual handling during test	• Automated assembly of optical and electronic components • Automated handling during tests	• On-chip integration of optical or optical and electronic functions
Passive Optical Components	• Manual assembly and alignment of micro-optics • Manual pigtailing of planar devices	• Automated precision alignment, assembly and pigtailing • Similar to device packaging processes • Integrable isolators and polarizers	• Higher functionality
Optical Connectors/Fiber	• Low-cost fiber • High-cost/high-precision connectors • Complex, demanding assembly	• Low-cost material and assembly of connectors • Low-labor fiber termination during installation • Fiber processes suitable for low-cost interconnect	

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V. Summaries of the Workshop Breakout Sessions

Summary of the Materials Breakout Session for the Workshop on Optoelectronics & Optomechanical Manufacturing, February 15, 1995 Advanced Technology Program - NIST

Members from industry, academia, and government (NIST) flocked to this session to discuss the optoelectronics (O/E) industry from the materials perspective. All in attendance were challenged to focus on our industry by answering the following questions concerning the state of optoelectronic materials: where are we now?; where do we want to be in 7-8 years?; how do we get there?; and what is industry's level of commitment? The following is a brief précis on the discussions that ensued for each inquiry.

Where are we now?

The feeling that "we have a long way to go" was unanimously shared by all participants. The industry is mature in many areas, yet there is much knowledge about materials that still must be garnered if O/E firms are to make low cost/high volume device components. Yet, many of the professionals present felt that O/E materials were caught in a "catch-22"; as device dimensions decrease, and increased device performance is desired, materials specifications are being pushed to the envelope. Coupled to an environment where manufacturing output is a paramount priority, material engineers have little time to devote to proper characterization and study of precursors, solders, and substrates. Participants also felt that device designers had little sympathy for the importance of materials, except that they demand "the best material available". Participants were clearly vocal that NIST had "dropped the ball" in the arena of optoelectronic materials standards. Other important points:

- O/E materials include substrates, bonding solders, dielectrics, and organometallic precursors - all which vary in quality from poor to good,
- State of materials is still at "trial & error" stage,
- Source purity (how pure?; how do you measure?) and source availability (only Japanese suppliers for some materials - a concern in some sectors),
- Materials effect all industries in this growth period - flat panel displays, lasers, MOCVD suppliers,
- O/E materials more complex than silicon,
- Decreasing number of large O/E players; will this affect O/E supplier quality?,
- With shrinking military funding, will the flat panel industry survive?

Where do we want to be in 7-8 years?

"In business!!!" was the answer that resounded throughout the discussion. Many shared the opinion that materials are the key driver for future devices; the better the materials, the greater the impact on device yields (the importance of materials growth and processing on yield also was discussed during the session). Three main areas where

enhanced focus is needed were identified: materials purity, materials growth, and materials processing. More specifically:

- Establishment of an optoelectronics grade of materials,
- Achieve the same learning curve effects and body of knowledge as silicon: e.g. the III-V's (particularly InP),
- Intelligent MOCVD; use of feedback control and expert systems for improved crystal growth,
- Optoelectronic standards for materials; i.e. greater involvement by NIST in this area,
- O/E standards for cleaning of materials,
- Replacements sought for ozone depleting chemicals
- In-situ measurements of epilayer thickness, composition, substrate temperature.

How do we get there?

The size of the O/E industry is small relative to the silicon industry. Thus the industry does not have sufficient buying power to push the desired materials objectives. Participants felt strongly that they needed to communicate more among themselves, as well as government (ATP?), in assisting in the effort to establish O/E standards. and facilitate communication in the O/E industry. OIDA is also expected to play a important role. Other points that were made:

- O/E specifications for materials,
- Design rules for III-V materials,
- Industry prioritize what materials are important; e.g. nitrides, III-V's.
- Industrial willingness to share material requirements with NIST,
- NIST must work with industry to develop optoelectronic grade standards for starting materials.

What is industry's level of commitment?

The optoelectronics industry is fragmented, with many small players, and a multitude of technologies. In many instances, these technologies are immature and *de facto* standards exist. There is always concern, especially among the smaller companies, that the vertically integrated Japanese companies will use their economies of scope to achieve superiority in materials, and drive U.S. companies out of the marketplace. Of equal concern is that there is no major company, analogous to Microsoft in software, which can temper the threat of foreign competition.

Attendees

Paul Berger - Univ. of Delaware
Chyi Chern - EMCORE Corp.
Gus Derkits - AT&T Optoelectronics
Dan Dummer - NIST

Albert Feldman - NIST
Robin Gilbert - American Display Consortium
Debbie Kaiser - NIST
Nasser Karan - Spire Corp.
Victor McCrary - Advanced Technology Program, NIST - Session Co-Chair
Albert Paul - NIST - Session Co-Chair
Henry Randolph - Westinghouse
Sebastian Raoux - Lawrence Berkeley Labs
Ed Renfer - Laser Photonics
Lawrence Robbins - NIST
Lawrence Rotter - NIST - Session Co-Chair
Michael Schen - NIST
J. D. Schermerhorn - ElectroPlasma
L. J. Schioler - SI Diamond
Michael Shimazu - Molecular OptoElectronics
Leo Schowalter - RPI
James Singletary - JPL
Kai Wong - Air Products

Break-Out Session on Design/Modeling.

ATP Workshop on Optoelectronics and Optomechanics Manufacturing

February 15, 1995

Herbert Bennett and Janet Marshall
Submitted February 27, 1995

Attendees

Herbert Bennett	NIST, Co-Moderator
Peter Ham	University of Maryland
Sergej Krivoshlykov	Ceramoptec, Inc
Janet Marshall	NIST, Co-Moderator
Scott Merit	University of Maryland
Dietrich Meyerhofer	David Sarnoff Research Center
Alex Wei	University of Maryland

A fourth person from the University of Maryland attended the last third of this session. Also, Sergej Krivoshlykov is from Russia. His company, Ceramoptec, Inc, East Longmeadows, MA does not support CAD for optoelectronics, but he has an interest in CAD and works on it at home.

CAVEAT: As happens in breakout sessions of this type, some statements are made that need to be verified. This report may have remarks that are not correct. It is only an attempt to convey what was discussed (with possible additional input).

WHERE ARE WE NOW ?

Because there is no product on the market yet that has an essential need for a CAD tool, currently there is only a limited amount of analysis software and no design software. In the future, there should be a need for simulating diodes [1], LED's, optical heads and software for making masks.

Existing modules are fragmented, limited in number, and do not efficiently connect together. They involve too many input parameters that have not been validated. Adachi's work in the earlier 1980's remains among the best source of such data. But, it may not be completely relevant for today's devices. The question "Are these input parameters still valid ?" arises. For these reasons, it is

difficult to sell the few existing software programs, even at the price of a few thousand dollars [4].

There is no commercially successful vendor of modelling and simulation tools for the optoelectronics industry. David Sarnoff's modules are hard to sell at $1-2k per module. The ARPA funded program at David Sarnoff Research Center contributed to developing the needed infrastructure and framework for connecting modules together; but there is no commercial product at this point. One reason for this is that no standards and consensus based framework for interconnecting modules exist for the optoelectronics industry [5]. Also, the ARPA funded work in this area was not commercially driven.

David Sarnoff's software runs on a SUN and this hardware is thought by some people to be too expensive; particularly for those companies with minimal profits from their optoelectronic products. Even with such hardware and software, the optimizations are done by hand because there are too many parameters involved. A PC environment would be less expensive and would be welcomed by many; particularly those at universities. Computer platform infrastructure is needed to overcome this hurdle for standardization.

The areas of concern for CAD are LEDs, diodes, optical heads, and software for making masks [6].

The attendees asked whether CAD tools were needed ? They thought that CAD tools are not needed for making a few laser diodes or light emitting diodes. However, CAD tools will be needed for higher level integration therefore let's get this going. The attendees were interested in whether or not HP, the world's leader in mass producing LEDs last year, uses CAD tools to design its LEDs. Also, the attendees asked whether the MOSIS-like place for optoelectronic devices in Japan uses or needs CAD tools to be successful.

WHERE DO WE WANT TO BE IN 7-8 YEARS ?

CAD for optoelectronics will be a much greater challenge than CAD for silicon based ICs. Optoelectronic simulators have to include many more physical mechanisms than do electronic simulators. Optoelectronic simulators have to include lasers, waveguides, modulators, and amplifiers. They have to treat many more interactions in addition to those among photons and carriers; boundary conditions are quantitatively more crucial; non-linear phenomena dominate; and carrier recombination is critical. In 7 to 8 years these complicating features have to be brought together in the context of a consensus based framework.

We want to have the above problems solved, if possible.

HOW DO WE GET THERE ?

In order to get there, we need to have standardized formats and protocols and a consensus based computer framework that is compatible with modules from different vendors and that is extensible

in time.

Another need is to have automated CAD tools that would produce the design for the first generation or first iteration of a device or product. These CAD tools will have to be verified, calibrated, and bench-marked in order to be accepted for use in manufacturing.

Perhaps better input parameters for describing complex refractive indices, photon and carrier transport in electromagnetic fields, beam propagation, and diffraction will be required for the predictive success of CAD tools.

Past experience from the semiconductor industry tells us that a stable market is needed to provide the essential resources for developing and implementing user friendly optoelectronic CAD tools and to create the awareness of the role that CAD tools play in gaining market share.

Some feel that it is too risky to undertake the development of CAD tools for an immature industry like optoelectronics. It may take 2 to 3 years to develop a tool. During this time, a different substrate, which is deemed a better choice for the device of interest, may be selected. If that occurs then to what extent will the CAD tool still be valid?

Large reductions in cost of optoelectronic devices may be possible with significant improvements in the design process. However, the devices are not there yet [7].

WHAT IS AN ESTIMATED LEVEL OF INDUSTRY COMMITMENT TO THIS AREA ?

Industry is interested. But, the profits margins are so small that the immature optoelectronics industry in the U.S. does not have adequate money and resources to invest in CAD tools. As a result, the U.S. optoelectronics industry's commitment to this area is sparse, tentative, limited, and fragmented.

The number of people from industry who attended this break-out session is one measure of industry's commitment to this area. It also suggests where this area ranks, and how things stand in the general scheme of things.

Another measure of industry's commitment is the fact that it is difficult for university students who have worked on optoelectronic design and modeling to find jobs.

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[1] KEYS (linKing softwarE to analYze waferS) [2] and Magic and/or L-Edit can do this given the appropriate platform. KEYS is the one-dimensional infrastructure that was developed at NIST which links the software packages SUXES (Standford University eXtractor of modEl parameterS),

SPICE (a Simulation Program with Integrated Circuit Emphasis), and STAT2. Given data points for individual devices, SUXES obtains the model parameters for SPICE. SPICE predicts the behavior of an individual device or an entire circuit. After analyzing each test chip on a wafer, STAT2 determines correlation coefficients and generates wafer maps of selected parameters. These wafer maps are valuable to the designer, modeler, and process engineer. A "standard wafer" design can also be obtained from NIST [3]. By modifying the technology file for this designed wafer which has been demonstrated at NIST, chips can be designed for many different technologies including NMOS, PMOS, CMOS, SOI/SIMOX, GaAs, and others.

[2] Marshall, J.C., and Mattis, R.L., Semiconductor Measurement Technology: Evaluating a Chip, Wafer, or Lot Using SUXES, SPICE, and STAT2, NIST Special Publication 400-90 (April 1992).

[3] Marshall, J.C., and Zaghloul, M.E., Semiconductor Measurement Technology: Design and Testing Guides for the CMOS and Lateral Bipolar-on-SOI Test Library, NIST Special Publication 400-93 (March 1994).

[4] Using a program similar to the SUXES program found in KEYS will help adjust these parameters to give a best fit. It is also difficult to advertise and distribute those software programs that are free.

[5] Therefore perhaps they can be included in the KEYS based framework.

[6] The Magic CAD tool that can be used for the "standard wafer design" generates data that can be used by the mask makers.

[7] In the infrastructure of an ideal design/simulating/process verification check it appears that more than one simulation tool is needed. Perhaps the one dimensional KEYS based framework can now be expanded to two or more dimensions. Once again it needs to be transportable to different platforms.

Summary of Devices and Components Breakout Session
ATP Optoelectronics Workshop - 2/15/95

Roughly two dozen people participated in the devices and components breakout session. Only two individuals, however, seemed to have any real knowledge of manufacturing (either custom or high-volume). Most people were more interested in an ATP program concentrating on current US strengths, such as new device development, and not weaknesses, such as high-volume, low-cost manufacturing. This schism divided neatly between those that knew something of manufacturing, and those that did not. The latter seemed to want to have a US infrastructure capable of cheap, low-volume custom production runs of devices of their design, but did not personally want to participate in such a program.

From those more attuned to manufacturing, there was a desire to have the optoelectronics community follow a development path similar to that taken by the silicon IC industry. They suggested the development of technologies to abstract the design and layout of optoelectronic devices and components from the physical processes that create them, similar to current CAD systems for silicon CMOS. In addition, they wanted to see the level of integration pushed so that optoelectronics might enjoy a growth in integrated functionality similar again to the silicon IC industry. One suggestion from the ranks of people unfamiliar with manufacturing was that a foundry system similar to the MOSIS analog and digital IC contract fab capability be developed for optoelectronics. This individual was unaware that NIST has just brokered a deal, in conjunction with the Japanese government, for just such a service. The same person also viewed such a capability as sufficient manufacturing infrastructure for his own needs. However, MOSIS is only intended as a prototyping facility for universities and small start-ups; it was never intended to meet the custom production fab needs of an entire industry. Similarly, such a capability should not be viewed as sufficient for the optoelectronics industry.

Much of the remainder of the discussions ended up focusing on the pet device technologies of the various participants. These ranged from medical waveguide technologies to smart pixel cameras. In all cases, there seemed to be little thought as to how the device would get to production for mass market commodities, and little appreciation for the efforts that a necessary to ensure high-yield, high-throughput production. These individuals voiced the opinion that it was inappropriate for ATP to consider manufacturing technologies that will be important in 5 to 7 years, as they had no idea what devices were really going to be important in that time frame. In the end, the group essentially agreed to disagree as to whether ATP should focus on manufacturing technologies in the optoelectronics industry (despite the use of "Manufacturing" explicitly in the title, many participants did not realize that this was the intended focus of the workshop). Near the end, a participant from the US Army Night Vision Center in New Jersey made a comment that she thought the program sounded similar to the ARPA's MANTECH, but felt that the optoelectronics industry was too immature (in the US) for such an effort at this time. Clearly, the preponderance of participants seemed to reflect this point.

Business/Economic Issues Breakout Session

Summary

The group agreed that a focus program in optical/electro-optical manufacturing could have a large potential economic impact on the U.S. economy. The potential economic impact would be dependent on the program scope. The group could not reach a consensus on whether a focussed program concentrating on developing optical component technology (referred to as the "front end") would have greater impact than a focussed program which emphasized tasks such as fabrication, assembly, and packaging (referred to as the "back end")

Those group members championing optical components maintain that those tasks associated with the "back end" are already lost to overseas competitors, and that no technology, which could be developed under an ATP focussed program would change this. Their strategic approach is that we concentrate our efforts on the high value-added "front end" components, which would keep the U.S. photonics industry at least one step ahead of the competition in terms of whatever performance parameter or parameters are important to the end-user.

Those group members championing the "back end" say that these areas are a significant fraction of the overall cost of any optical/electro-optical product, and have been generally neglected in R&D funding. To date, it is more cost effective to perform design domestically, but perform the fabrication, assembly, and packaging abroad for all but the high price, high performance applications.

The moderator brought up for discussion, some of the ideas in the submitted white papers concerning new business opportunities based on new end-user requirements for opto-electronic components and systems which are on the order on micron size.

For conventionally sized, low cost, high volume, opto-electronic components and systems, where labor is a nominal percentage of the cost, it has made business sense to have labor intensive tasks such as fabrication and assembly be performed in low wage countries. As the dimensions of the opto-electronic components approach micron size, the human eye and human hand will no longer be accurate enough to perform a number of the fabrication and assembly tasks. It opens up an opportunity for automated and semi-automated machines to be developed for these tasks. In this scenario, labor costs as a percentage of the total cost would shrink to the point where low cost, high volume optical and electro-optical components could be manufactured in the U.S.

Again the group had diverging opinions. The individuals who favored the "front-end" R&D, maintained that any automated and semi-automated equipment eventually commercialized from an ATP focus program, would be used in overseas manufacturing plants. The individuals who favored the "back-end" R&D believed that automated and semi-automated equipment for micron size optics, was a potential scenario for having high volume, low cost optical and electro-optical components work being performed in the U.S.

The group discussed the dynamics of the photonics industry and how ATP support could make a difference. The group believed that the majority of optical/electro-optical firms in the U.S. are

relatively small companies, who looked to market to low-volume, high-margin niches. These firms have no money to develop a manufacturing infrastructure on their own. Some of the larger companies which develop opto-electronic components have varying degrees of manufacturing infrastructure in place, but have no incentive to transfer the technology to smaller companies. Also in some of the larger companies which develop high volume, low cost components, they choose to perform several aspects of their manufacturing overseas for business reasons.

ATP funding could make a difference in creating a critical mass of R&D in optical/opto-electronics manufacturing. It could benefit a great number of companies in a very fragmented marketplace. The group members said that ATP could also accelerate the adoption of new technology by small firms.

<u>List of Attendees</u>
Phillippe Becker - AT&T Bell Laboratories
Phillip Congdon - Texas Instruments
Michael Daum - NIST/ATP
J. Terrance Flynn - Kodak
Carlos Grinspon - NIST/ATP
Roland Haitz - Hewlett Packard
Robert Klaiber - AT&T Bell Laboratories
Erik Kreifeldt - Optical Society of America
Jeffrey Radke - Honeywell
Carl Smothers - Texas Instruments